Using Archaeological Remote Sensing to Evaluate Land Use and Constructed Space in Chaco Canyon

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USING ARCHAEOLOGICAL REMOTE SENSING TO EVALUATE LAND USE AND CONSTRUCTED SPACE IN CHACO CANYON

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DISSERTATION

Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy
Anthropology

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DEDICATION

For my daughter, Lucia Grace. You are the greatest reminder that studying the past means nothing without the future.
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ARCHAEOLOGICAL REMOTE SENSING TO EVALUATE LAND USE AND CONSTRUCTED SPACE IN CHACO CANYON

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ABSTRACT

Archaeological remote sensing includes a suite of non-invasive methods that can be used to study elements of the archaeological record that may not be achievable otherwise.

Using primarily geophysical remote sensing, and especially ground-penetrating radar (GPR), three studies involving questions of “use” were conducted in Chaco Canyon, New Mexico. The first used GPR to study the built interior features of a single room in Pueblo Bonito to evaluate use and function of that room. Three categories of features were identified in the GPR data and confirmed with subsequent excavation. The second study used GPR to re-evaluate an enigmatic land use feature located near one of the canyon’s great houses. A complex series of features were identified below the surface pattern characteristic of this feature, suggesting it represents a series of building episodes.

Finally, an expanded remote sensing approach, including GPR, magnetometry, and aerial photography, was used at a multi-site scale to evaluate land use patterns from the perspective that they served as part of an agricultural system. Results show that while land use patterns are prevalent, they do not conform to the patterns predicted in previous models.
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Chapter 1 - Introduction

Archaeological remote sensing incorporates a suite of methods designed to measure various properties of materials, sites, and landscapes in ways that are not achievable otherwise. The range of techniques that fall under the “archaeological remote sensing” definition, from airborne laser scanning to ground-based geophysics, have undergone dramatic technological advances in the past decade that in turn have had profound impacts on the way sites are discovered and imaged. With these technological advances has come a parallel change in the ethos of the discipline: the call to develop frameworks to contextualize remote sensing applications within the process of archaeological interpretations.

This dissertation evaluates archaeological remote sensing as a means for understanding land use and constructed space during the Bonito Phase (ca. A.D. 850-1150) in Chaco Canyon, New Mexico (Figure 1.1). Two primary archaeological questions are addressed through this research: the identification of built interior room features to evaluate use and function of an interior pueblo room, and the evaluation of land modification patterns from the perspective that they served as part of a broader system of agricultural land use. The studies that comprise this dissertation encompass three different scales, from an individual pueblo room, to a single enigmatic built feature near one of the canyon’s great houses, to a multi-site land use assessment along the canyon floor. All address some aspect of “use” (whether use of an individual room or use of land near major sites), and all are linked by the goal of broadening our understanding of Chaco’s prehistory using geophysical remote sensing as a primary source of data. To
this end, this is a solution-oriented dissertation that attempts to offer methodological strategies throughout its chapters for using remote sensing and geospatial methods to address both logistical and archaeological problems.

The outcomes of this dissertation are threefold. First, this dissertation contributes new empirical data on the buried infrastructure in the main part of the canyon floor, thus helping elucidate how land use was practiced in-between some of the great houses. The majority of Chaco scholarship has traditionally focused on either the great houses and their associated material culture or features visible on the surface of the landscape. While these studies have been immensely important, they do not account for the many cultural activities that lead to the modification and ultimate burial of many features. New data, such as those generated by this research, help evaluate ideas of land modification as it relates to the growth of an agriculturally dependent emergent complex society (Sebastian 1991; Vivian 1990, 1992). Second, while substantial progress has been made in how aspects of the archaeological record such as prehistoric land use and interior spaces are identified, there are still key challenges associated with locating and characterizing the spatio-temporal patterns associated with the built environment (Munoz, et al. 2014; Nagendra, et al. 2004). This project utilizes advancements in geospatial and remote sensing technology in two specific ways: 1) to the challenge of mapping small buried interior room features, and 2) to the challenge of identifying the often subtle or even “invisible” patterns of prehistoric land modification. The non-invasive nature of these methods is an added benefit for acquiring new data while also adhering to the National Park Service’s mission of preservation. Third, this research has generated numerous directions for future research, thus helping establish it as an important stage in a multi-
tiered approach to studying land use and constructed space in Chaco. The geospatially accurate maps generated as part of this research can be used to effectively and efficiently guide future testing efforts, adding to the potential to transform the way land use and constructed space is studied in the canyon.

Figure 1.1: The main part of Chaco Canyon (part of Chaco Culture National Historical Park) with stars noting the specific study locations included as part of this dissertation.

Terminology and Methods Used in this Dissertation

The term “remote sensing” is generally used as an umbrella term to refer to a suite of methods that collects information about some phenomenon without coming into contact with it (Johnson 2006). This dissertation primarily deals with ground-based or geophysical remote sensing, which is a subset of methods derived from geophysical prospecting and adapted for archaeological investigations through rigorous field
collection techniques and data processing programs specifically developed for the study of the archaeological record (Clark 2003; Kvamme 2003). All geophysical methods measure changes in the ground related to the presence or absence of buried materials and are most effectively used in archaeology to map features within the first 5 meters of surface. Ground-penetrating radar (GPR), one of the more well-known geophysical methods used in archaeology, was the principal geophysical method used for this research. The GPR method uses radar energy to record reflections from physical and chemical changes in the subsurface. It has the unique advantage of allowing depth in the ground to be measured through velocity calculations, meaning that when data are collected in parallel transects in a grid, a three-dimensional picture of subsurface changes can be created (Conyers 2013). This dissertation also utilized magnetometry (or more accurately, magnetic gradiometry), which is another geophysical method that measures and records small changes in the Earth’s magnetic field that are affected by changes in buried soils and materials (Aspinall, et al. 2008; Witten 2006).

The research conducted for this dissertation also collected new high-resolution aerial data using low-altitude aerial photography from a helium balloon platform. These data were processed using structure from motion (SfM), a type of photogrammetric processing that turns many individual aerial photos into high resolution orthophotos and digital elevation models (DEMs) (Westoby, et al. 2012). This work also utilized legacy remote sensing data by analyzing and georeferencing historic aerial photographs for the canyon. In addition to these remote sensing techniques, other geospatial methods that fall just outside of the “remote sensing” definition were also critical to this work. Most prominently, the collection of sub-centimeter coordinate data using a real-time kinematic
global navigation satellite system (RTK GNSS) served as a crucial link between remote sensing data collected in the field and data analyzed in the lab. Finally, none of the analyses presented in this dissertation would have been possible without the use of a geodatabase, which is part of geographic information systems (GIS) to integrate and visualize the many different types of spatial data acquired. The methods used in this dissertation and how they were incorporated into an overall workflow is visualized in Figure 1.2.

Figure 1.2: The methods and workflow used in this dissertation.
Background: Geophysical Remote Sensing in American Archaeology

The utility of geophysical prospection for archaeological applications was probably first recognized in the early 20th century, when rudimentary geophysical surveys were used in Europe and later North America in an attempt to map buried cultural deposits (Conyers 2013; Gaffney and Gater 2003). It was not until the 1950s, however, that electrical, magnetic, and electromagnetic surveys were applied to archaeological sites in earnest, spurred in part by the technological developments from World War II (Cheetham 2008; Conyers 2013). Although much of this early work was pioneering, many of these early surveys were slow, cumbersome, and produced data that were fraught with processing and interpretative problems (Conyers 2013).

The use of remote sensing in American archaeology, including geophysics, entered the literature in earnest in the 1960s (Aitken 1961). However, it was the National Park Service (NPS) that played the most significant role in the development of early archaeological remote sensing in America. Through their creation of the Division of Remote Sensing, NPS facilitated some of the first problem-driven applications of archaeological remote sensing, many of which occurred in or around Chaco Canyon. The seminal volume edited by Thomas Lyons, Remote Sensing Experiments in Cultural Resource Studies: Non-destructive Methods of Archaeological Exploration, Survey, and Analysis (1976), presents some of these Chaco remote sensing studies, including the very first application of ground-penetrating radar in American archaeology (Vickers, et al. 1976).

The park service expanded their introduction of remote sensing in American archaeology with the publication of Remote Sensing: A Handbook for Archaeologists and
Cultural Resource Managers the following year (Lyons and Avery 1977). The main goal of this publication was to disseminate information about remote sensing in a way that was practical and accessible to archaeologists and that specifically focused on North America. Prior to these publications, much of the information about archaeological remote sensing came out of Europe. Ten supplements to this handbook were published between 1978-1985, focusing on different methods and regions throughout the United States. Two of these supplements include geophysics as part of the description of remote sensing methods in archaeology. Supplement 2 (Morain, et al. 1978) presents one of the first definitions of remote sensing in which geophysics is explicitly included. It observes that “in archaeology, we take considerable interest in buried structures and artifacts, objects that are not visible to the eye and quite probably not directly detectable using space or airborne sensors. This is the area in which ground based remote sensing plays a vital role” (Morain, et al. 1978:24). Supplement 3 (Lyons, et al. 1980) includes an extensive bibliography of remote sensing studies in anthropology, including several entries on geophysics.

Despite the pioneering efforts by the NPS Division of Remote Sensing, the widespread application of geophysics in archaeology would not really take off until the late 1980s, when the advent of faster and less expensive computers increased the ease and speed at which data could be collected and subsequently processed. This allowed much larger areas of ground to be covered with greater data density, resulting in more precise maps of ever-increasing spatial areas (Cheetham 2008; Conyers 2013; Gaffney and Gater 2003). As geophysical archaeology increased in popularity and accessibility, much of the work in the 1990s was geared towards testing and assessing the utility of geophysical
methods on different types of archaeological sites in a variety of environmental contexts (Johnson 2006). Most of the publications from this early work focused on the successes of surveys, often with spectacular images of buried features, while downplaying or ignoring the failures, shortcomings, or pitfalls of the survey. This led to a number of unfortunate misconceptions and misunderstandings within the general archaeological community, leading some to either erroneously believe one method works better than another, or even question the idea that these methods “work” for archaeology at all (Cheetham 2008; Conyers 2013). Geophysical applications in the 2000s were primarily aimed at correcting these misconceptions by firmly couching these methods in terms of their scientific principles. Many of the most seminal books and journal articles describing these methods, including their theoretical foundations, scientific framework, and their application to archaeology, were published during this decade (Aspinall, et al. 2008; Campana and Piro (editors) 2009; Clark 2003; Conyers 2004; Gaffney and Gater 2003; Johnson (editor) 2006; Kvamme 2003, 2008; Wiseman and El-Baz (editors) 2007; Witten 2006). Still, the primary emphasis in the use of these methods was in the “discovery and exploration” of archaeological materials.

In the past decade or so, a shifting attitude in geophysical archaeology has emphasized the interpretive value of geophysical data. While the prospection history of these methods continues to have utility, there is a new focus on using geophysical remote sensing data as primary datasets to directly address archaeological questions (Conyers and Leckebusch 2010; King, et al. 2011; Kvamme 2017; Opitz and Herrmann 2018; Thompson, et al. 2011). The shift to using archaeological remote sensing as part of a question driven approach has brought up new theoretical and methodological
considerations for the discipline, including data collection strategies, data access and archives, and data processing and interpretations (Opitz and Herrmann 2018:2). To this end, the ways in which geophysical remote sensing methods are applied to archaeological questions are continuously being developed. The studies included as part of this dissertation were designed with these goals in mind. All are framed in terms of their theoretical implications and all attempt to use remote sensing data to advance our understanding of Chacoan prehistory. By including methodological information on data collection and data processing/interpretation, this dissertation also aims to advance the theory of application related to contemporary archaeological remote sensing.

Organization and Overview of Dissertation

This dissertation follows the “hybrid” format, which substitutes published articles or manuscripts prepared for submission in place of a traditionally organized dissertation. As such, there will be overlap in some of the background and methods information between each chapter.

Chapter 2, “Micro-scale Mapping Using Ground-penetrating Radar: An Example From Room 28 in Pueblo Bonito” is co-authored with Dr. Patricia Crown and appears in the journal *Advances in Archaeological Practice* (2015). It presents a study where GPR was used to identify individual features within a single room within Chaco’s largest great house. GPR was conducted prior to the re-excavation of Room 28, which provided a unique opportunity to directly compare the GPR data with excavation results and thus evaluate how this method mapped features within a small (less than 8 x 3 m) interior space. Three categories of features within the room, posts/postholes, entryways, and
burned materials, were successfully identified in the GPR maps. These features are fundamental in understanding the use of Room 28, as they represent construction events, access points, and abandonment of this room. From this analysis, we developed a set of expectations for using GPR to identify similar features in other interior pueblo rooms. This strategy can be used to study other interior rooms throughout the American Southwest but has particular application to Chaco because of the restrictions on excavating other great house rooms.

Chapters 3 and 4 broaden the scale of GPR mapping to that of a large, singular built feature on the Chacoan landscape known as the Chetro Ketl field area. Located southeast of the Chetro Ketl great house, the Chetro Ketl field area is rectangular in shape with an interior gridded pattern visible in aerial photographs. Interest in the Chetro Ketl field area has been ongoing since it was first photographed by Charles Lindbergh in 1929. It was one of the original locations for the Division of Remote Sensing’s experiments in the early 1970s, including applications of both GPR and magnetometry. While it is most commonly interpreted as a series of agricultural fields that may have been connected to an extensive agricultural field system throughout the canyon (Vivian, et al. 2006), it has yet to be conclusively linked to food production. Numerous alternate explanations have been proposed for it (Stein, et al. 2007: 210), making it one of the most enigmatic examples of land modification within the canyon.

Initial GPR surveys were conducted in the field area with the goal of better understanding the nature of the grid patterns visible in aerial photographs. However, the results of these initial surveys were so unexpected that surveys were expanded throughout the field area over multiple field seasons. Primarily, the GPR data showed a complex set
of buried features below the grid pattern visible on the surface. Many of these patterns involve linear features with a distinct layout and orientation from the surficial grid pattern. These results are used to argue that the Chetro Ketl field area represents a palimpsest of activity rather than a single episode of land modification. Chapter 3, “A Remote Sensing Approach to Studying Land Use Change in Chaco Canyon,” contextualizes the Chetro Ketl field area in terms of understanding prehistoric land use in Chaco and proposes an overall approach for studying a feature of this size and complexity, particularly as it relates to the preservation mission of a National Park. It appears as a chapter in the volume edited by Duncan McKinnon and Bryan Haley, *Archaeological Remote Sensing in North America: Innovative Techniques for Anthropological Applications*. Chapter 4, “Using Ground-Penetrating Radar to Re-evaluate the Chetro Ketl Field Area in Chaco Canyon,” delves into the archaeological history of the Chetro Ketl field area. Previous excavation records were used to augment the interpretation of the GPR data, allowing a much more comprehensive analysis of the GPR results. This includes a detailed reconstruction of the possible building history of the Chetro Ketl field area. It appears in *Journal of Archaeological Science: Reports* (2016).

Chapter 5, “Evaluating the Gridded Agricultural Field Model in Chaco Canyon Using Geophysical Remote Sensing” is co-authored with Dr. W.H. Wills. It builds upon the work at the Chetro Ketl field area by using geophysical remote sensing at a multi-site scale to assess the prediction that other gridded fields exist in the canyon. This gridded agricultural field model was developed by R. Gwinn Vivian in the early 1970s as one of the explanations for how agriculture was organized within the canyon. According to the model, the control and management of numerous formalized gridded fields throughout
the canyon was critical to the evolution of social inequality during the Bonito Phase. The surface pattern seen at the Chetro Ketl field area is used as the prime example for the structure of these gridded fields. However, despite the prediction that these gridded fields are located throughout the canyon, locating them (or any agricultural fields) has been a long-standing challenge in Chacoan archaeology.

In addition to expanding work at the Chetro Ketl field area, two additional sites predicted to contain gridded fields, Casa Rinconada and Hungo Pavi, were tested using an expanded set of remote sensing methods. These included magnetometry, another geophysical remote sensing method, and low-altitude aerial photography from a helium balloon platform. Through this combination of remote sensing methods, numerous features and land use patterns were identified at all three of the study areas. Some elements of these patterns were similar across study areas, suggesting they may be related to the same phenomena. However, none showed the remarkable uniformity predicted in the gridded agricultural field model. We argue that if these newly identified patterns are connected to food production, then they attest to a diversity of agricultural strategies in the canyon rather than a singular formalized system.

Finally, Chapter 6 provides a synthesis of this dissertation’s main goals and identifies directions for future research.
Chapter 2 - Micro-scale Mapping Using Ground-penetrating Radar: An Example from Room 28, Pueblo Bonito

This chapter is adapted from a manuscript with the same title co-authored with Dr. Patricia Crown. The final version appears in 2015 in the journal Advances in Archaeological Practice 3(2):124-135.

Introduction

Pueblo Bonito is one of the most thoroughly excavated sites in Chaco Canyon, with major excavations in the 1890s by the Hyde Exploring Expedition and in the 1920s by the National Geographic Society. These excavations recovered some of the rarest and most spectacular assemblages found in Chaco, securing Pueblo Bonito’s rank as the most significant and culturally important site in the Ancestral Puebloan world (Neitzel 2003). Today, Pueblo Bonito is part of Chaco Cultural National Historical Park, administered by the U.S. National Park Service. Because part of the Park Service’s mission at Chaco is to preserve Pueblo Bonito, no major excavations have occurred there since 1927. What little has occurred has been in the context of architectural stabilization or collecting wood samples for dating (Neitzel 2003:7; Windes and Ford 1996). Differing priorities during the early excavations meant that data pertinent in modern archaeological research were not collected systematically, including, in some cases, the identification of stratigraphic layers and the recovery of datable materials that could be used to reconstruct the use and abandonment of particular rooms within the pueblo. For some rooms, it is unclear whether sterile contexts were reached. Therefore, the basis for interpreting the organization, population, and function of Pueblo Bonito is still primarily information
collected from excavations a century ago (Neitzel 2003:7). Generating new lines of evidence to help refine our existing knowledge requires new methodological strategies that adhere to the Park Service’s mission of preservation.

Ground-penetrating radar (GPR) has long been utilized as a method in the detection and mapping of cultural features (Conyers 2012, 2013; Gaffney 2008; Goodman and Piro 2013), with some of the first applications in American archaeology occurring in Chaco Canyon (Vickers and Dolphin 1975). While GPR has become a common tool for archaeological research, the specific type of application used in this project, in which a small room (less than 8 by 3 meters) is mapped and understood in terms of the larger pueblo, is less-tested. The purpose of this study was to evaluate the use of GPR in assessing the construction history and room function of a single room (Room 28) within Pueblo Bonito. Furthermore, in the past several years, geophysical archaeologists have increasingly emphasized the interpretive value of GPR data in answering archaeological research questions (Conyers and Leckebusch 2010; Thompson, et al. 2011). To this end, the ways in which methods such as GPR are applied to answer archaeological questions are continuously being developed, and this project was conducted with this as a goal.

First excavated in 1896 by the Hyde Exploring Expedition, Room 28 (Figure 2.1) produced the largest and most significant assemblage of ceramic cylinder jars ever found in the American Southwest (Crown 2012; Judd 1964; Pepper 1920). Organic residue analysis demonstrates that cylinder vessels were used for drinking a cacao beverage, providing important insight into Chaco’s relationship with Mesoamerica (Crown and Hurst 2009). Original photographs, notes, and the published description indicated that the
room burned, suggesting that datable material might have been left in the room. GPR mapping was conducted a year prior to excavation to evaluate depth of excavations, whether earlier surfaces were visible, and what the room was backfilled with in 1896. Co-author Patricia Crown designed the re-excavation of Room 28 in the summer of 2013 to determine where the cylinder jars (and other vessels) had been placed within the room, when the room was constructed, the nature of the burning of the room/vessels, and whether earlier floor surfaces underlay the surface reached in 1896. Ultimately, this rare excavation at Pueblo Bonito provided an opportunity to compare the GPR data and the excavation results to evaluate how GPR mapped certain features in this small space.

Figure 2.1: Plan view of Pueblo Bonito with Room 28 outlined. Image adapted from Judd’s (1964:Figures 2-6) site plan map.
Here we show how three categories of interior room features, posts/postholes, entryways, and burned layers, were successfully mapped with GPR and confirmed with excavation. These features are critical in understanding the use of Room 28, as they represent construction events, access points, and abandonment of this room. By identifying the geophysical signature of features pertinent to the construction and use of Room 28, we offer a strategy for studying other rooms within Pueblo Bonito. In addition, because architectural features such as postholes and entryways are not unique to Pueblo Bonito, it is anticipated that this approach will have applicability in the wider Southwest. We also address some of the challenges inherent in this type of survey, and other ways to improve future studies.

GPR Use in Archaeology and the American Southwest: Background

Archaeologists have employed GPR with great success in many parts of the American Southwest for many years (Conyers and Cameron 1998; Conyers and Osburn 2006; Ernenwein 2006; Liebmann 2012:104-105; Sternberg and McGill 1995; Vickers and Dolphin 1975). The success of GPR is dependent on the physical and chemical contrast between the archaeological feature of interest and the soils/sediments surrounding it. For example, a masonry wall in a sandy context will often show up quite well with radar due to a high contrast between the materials, while dry adobe walls in dry sediments have such similar physical and chemical properties that they may be virtually invisible with radar (Conyers 2012). In Chaco Canyon, the prevalence of sandstone masonry archaeological features in dry, mostly sandy sediments has proven to offer an excellent environment for GPR mapping.
While all shallow subsurface geophysical methods are to some extent mapping the physical and chemical changes in the ground, the GPR method has the distinct advantage of allowing actual depth analysis by measuring velocity. This means that, while other methods such as magnetometry or resistivity are mapping and averaging information from a single, often unspecified volume of subsurface, the GPR method allows the researcher to accurately discriminate between specific buried layers (Conyers 2013; Goodman and Piro 2013). This is because GPR transmits pulses of electromagnetic energy into the ground, and measures the time it takes for those pulses to reflect off some buried object or interface and return to the surface. Through velocity analysis, this transmission and reflection of energy can be converted to actual distance, or depth, in the ground. The result is that three-dimensional, layered images can be generated showing the spatial distribution of cultural features within a specific area (Figure 2.2).
Typical modern-day applications of GPR in archaeology involve a landscape-based approach, in which multiple sites or large areas are mapped, analyzed, and interpreted in a site-wide or sub-regional context (Conyers 2009; Kvamme 2003; Thompson, et al. 2014). This type of approach reflects both the increasing sophistication of the technology that has allowed researchers to conduct surveys on the scale of hundreds of meters in a single day, as well as the recognition that meaningful
interpretations can often be made about sites in which multiple features are mapped and imaged (Conyers and Leckebusch 2010; King, et al. 2011; Kvamme 2003). Taking this approach in the American Southwest, features such as walls, rooms, hearths, and kivas are understood in terms of their size, layout, and spatial relationships to other features, which can lend insight into the architectural construction, use-life, and organizational significance of sites. Arguably, these types of macro-scale landscape approaches are some of the most efficient and powerful uses of any type of geophysical survey in archaeology (Burks and Cook 2011; Gaffney 2008; King, et al. 2011; Thompson, et al. 2014).

Landscape-scale approaches often hinge on the ability to recognize patterns within the spatially interpolated data across a given area. A common survey strategy is to cover an area appreciably larger than the hypothesized feature being targeted (Conyers 2013). This not only ensures that the overall spatial extent of the feature is mapped, but also allows the analyst to recognize patterns of reflections that may constitute the feature (Kvamme 2008). A far less common application of the GPR method in archaeology, and particularly in the American Southwest, is mapping small room interiors within larger sites. In this type of survey, the archaeologist is challenged with the task of identifying small, single, interior room features without relying on the overall pattern recognition that comes from spatially expansive surveys (Kvamme 2008). Using GPR for small-space, or micro-scale, mapping rests on the ability to identify sets of reflections that may relate to specific features of interest such as floor surfaces, areas of burning, benches, hearths, or postholes, all of which may help understand the function, use, or abandonment of that specific room. Ideally, this information can then be put into broader context at the scale
of the site or pueblo, helping to determine possible inter-site variation or function over time.

The challenge with this type of approach is the scale at which the survey takes place. While the dimensions of rooms in pueblos vary greatly, it is common for rooms to measure only a few meters in one dimension (Hegmon 1989; Lekson 1986; Windes 2003). From the surface, Room 28 in Pueblo Bonito measures just under eight meters in length and approximately 2.75 meters in width. The photographs taken during the 1896 excavations lack a scale, so room depth was unknown. The desire for a detailed, high resolution depth analysis within a restrictive physical space made GPR the most applicable geophysical method for this project. With a goal of achieving at least two meters in depth and an object resolution of about 10 cm, a GSSI 400 MHz antenna was utilized with the SIR-3000 system. A total of eleven transects were collected in summer 2012 at a spacing of .25 meters (a total of 2.75 meters, the width of the room), and measuring approximately eight meters in length (the length of the room on the surface, which overlies earlier Rooms 28 and 28a).

**Results of Excavations and GPR Analysis**

Over the course of its history (A.D. 800s through the 1200s), Pueblo Bonito was remodeled multiple times. Some rooms were abandoned or repurposed, other rooms were expanded, and new rooms were added to the pueblo (Lekson 1986:127; Windes 2003). Untangling the complicated construction history and use-life of this site has been accomplished through massive dating efforts (Windes and Ford 1996) and detailed architectural analyses (Judd 1964; Lekson 1986). From these studies, we have a number
of clues as to what kinds of architectural features might be expected in a room, and how that relates to a room's potential function and Pueblo Bonito’s construction history. Three types of architectural features were uncovered in the 2013 excavation of Room 28 that could also be interpreted in the GPR images. These were: entryways/doorways, postholes/posts, and burned rocks/stratigraphic layers (Sturm 2012). Each of these feature types are generally known to have significance in the construction history of Pueblo Bonito, and so identifying them in a specific room is a way to study use and construction at the level of an individual room (Lekson 1986). Comparing the excavations of Room 28 to the GPR maps also allowed us to verify how and to what extent the GPR method was mapping features in this small space.

To assess what types of features could be mapped with GPR, the GPR data were processed to generate reflection profiles and amplitude slice-maps. Reflection profiles show the vertical structure of GPR reflections in profile view (Conyers 2013). These are important interpretative tools in GPR data analysis because they show the geometry and strength of reflections, which helps to determine what types of materials and subsurface properties are generating those reflections. For example, in this project, burned sandstone in the room generated higher amplitude reflections that were clearly visible in the reflection profiles and corroborated through excavation. The reflection profiles were minimally processed to preserve as many reflections as possible, and only a background filter was applied to remove extraneous system "noise" (Conyers 2013:123-125).

In addition to reflection profiles, the data were post-processed to generate amplitude slice-maps. These maps, which compare the reflections recorded in one transect to those recorded in adjacent transects, are often powerful visualizations of
changes in reflections across a given area and at various depths in the ground (Conyers 2013; Goodman and Piro 2013) (Figure 2.3). What these maps are not, however, are one-to-one realizations of buried features. The initial generation of these maps missed numerous features that were revealed through excavation. To see if additional features could be imaged, the amplitude slice-maps were re-processed several times using different settings until as many buried features as possible were imaged. The final best effort utilized a high data sampling rate and smaller weighted distance using an inverse distance weighted interpolation method (Figure 2.3). Below we describe the materials that generated the GPR reflections associated with each feature and how they were identified in the reflection profiles and the final amplitude slice-maps.

Figure 2.3: 3D animation of GPR data collected in Room 28, starting at ground surface and moving deeper into the ground. Changes in reflections related to postholes, entryways, and burned materials are seen as higher amplitude reflections (red, yellow, and black). North is up.
**Entryways**

Three entryways were uncovered in the 1896 excavations, two connecting Room 28 with Rooms 32 and 51a to the north and one connecting Room 28 with the plaza area to the south. All three were entirely buried with backfill. Because the buried entryways were built into the walls of the room, it was initially unclear if GPR mapping would image them in a meaningful way. When the GPR data were reanalyzed after excavation, however, it was clear that the entryways were visible in the reflection profiles as distinct vertically linear “breaks” or truncations in the stratigraphy of higher amplitude than the matrix surrounding them (Figure 2.4). The strong planar reflections above the entryway in Figure 2.4 represent the fill material from this entryway, including large stone slabs that appear to have been partially burned. The ability of the GPR method to map features within a vertical wall is possible because of the conical shape of the radar energy transmission, meaning the areas immediately in front, behind, and on either side of the antenna are reflected by the radar energy. By pulling a GPR transect directly next to a wall, the radar energy penetrates down and to the sides of the antenna, thereby reflecting the wall itself, and in this case, entryways built into the wall. In addition to being visible in the reflection profiles, all three entryways are apparent on the amplitude slice-maps as areas of higher amplitude reflections (Figure 2.5). The strength of these amplitudes is likely due to several factors, including disturbed fill material within the entryways and partial void spaces that exist within that fill.

From previous archaeological work conducted at Pueblo Bonito, it is known that the majority of doorways within the pueblo connect one interior room to another (Lekson 1986:28). In the older section of the pueblo (where Room 28 is located), doorway
patterns seem to be irregular, leading to the assumption that there was an extensive rebuilding and reuse of rooms in this part of the pueblo (Lekson 1986:132). Locating the doorways within rooms and determining which rooms or spaces they connected to, is therefore an important way to determine access, connectivity and possibly even room function (whether storage or habitation).

Figure 2.4: GPR reflection profile showing the reflections from several features located near the northern wall of the room. These include the cut and fill associated with two entryways into adjacent pueblo rooms, burned materials, and a burned post.
Figure 2.5: Two amplitude slice-maps representing two different depths in the ground, showing the reflections from seven posts/postholes and three entryways in Room 28. The southern entryway is highly visible in the slice-maps due to numerous large rocks that were used to fill the entryway. The reflections from a metal can, left during the 1896 excavation, and a stone are also seen at these depths.

**Posts and Postholes**

A total of seven postholes were uncovered on the floor surface of the room during re-excavation of Room 28 (Figures 2.5 and 2.6). Six of these holes are visible in the GPR
maps, though with varying degrees of resolution. One key variable in imaging these postholes appears to be the presence of a sandstone lining within the post hole. All of these postholes were lined with cobble-sized sandstone slabs with lignite filling the gaps between the rocks (Figure 2.7). The only floor posthole that was not visible was also the only unlined posthole. As seen in Figure 2.5, there are a handful of other reflections at this depth that share a similar amplitude and isolated circular appearance and could easily be misinterpreted as postholes. Instead, excavation determined that these "extraneous" reflections were stones, or in the case of the reflection near the entryway in the south wall, a metal can left behind by the 1896 excavators. While interesting, these non-post reflections somewhat obscure the interpretive value of these maps. In addition, one large posthole that was built into the northern wall of Room 28 and lined with plaster is visible in the GPR reflection profiles (Figure 2.8). This posthole, PH 15, is seen in the reflection profile as a narrow vertical break in the stratigraphy, with a slight hyperbolic shape and higher amplitude than the sediments on either side of it. It is likely that this posthole is visible in the reflection profiles both because it was partially burned and because it is fairly substantial in size (over 20 cm in diameter), creating a large gap in the sandstone masonry wall.
Figure 2.6: Room 28 at the base of excavation, (approximately 2.4 m in depth), showing some of the major postholes located in the floor surface. The remaining postholes are obscured by the screw jacks, which stabilized the fragile pueblo walls. North is to the right.

Figure 2.7: Close-up of Posthole 3 (PH 3), with burned materials visible within and surrounding the hole.
**Burned Materials**

Burned materials, both within postholes and as sediment layers or sandstone slabs, were perhaps the most obvious features in the GPR reflection profiles and slice-maps (Figures 2.2 and 2.8). Burning episodes fundamentally alter the physical properties of sediments by oxidizing iron minerals, which in large or concentrated quantities can be detectable with GPR (Conyers 2013). In the case of Room 28, the room burned before it fell into disuse, making burned material of particular interest in studying the abandonment of this room and marking an important shift in use of space within Pueblo Bonito. The area marked in Figure 2.2 as “Reflections from burned sediments,” was highly oxidized with some lumps of vitrified sand. The ability to map burned stratigraphic layers and materials is important when studying the use and abandonments of specific rooms within a larger site.
Figure 2.8: Photo of the northern wall of Room 28 as exposed during excavations compared to the GPR reflections profile that was collected directly next to this wall. The area of the GPR profile, which corresponds to the wall, is outlined by a red box. From the surface, the GPR energy was able to penetrate down and to the side to generate reflections from important architectural features, including a doorway into an adjacent room, a burned post, and burned sandstone.

Discussion: Challenges and Benefits of Micro-scale GPR Survey

The use of GPR mapping to conduct an analysis of cultural features at the level of an individual pueblo room proved to have numerous benefits as well as challenges that were specific to this scale of survey. The three most restrictive elements of a micro-scale GPR survey are identified as: 1) the increased difficulty in identifying and interpreting
features of interest, 2) the resolution/depth penetration tradeoff associated with antenna frequency, and 3) equipment maneuverability/data collection strategy.

First, even with the high-resolution mapping capabilities of the GPR method, there are inherent principles in collecting and displaying digital data that will affect the kinds of interpretations that can be made. This is particularly true in relation to the amplitude slice-maps, in which a number of data points are reduced, averaged, and then spatially interpolated to generalize the patterns of reflections across a given space (Conyers 2013; Goodman and Piro 2013). In a survey such as this, reducing and interpolating the data means there is high possibility of "removing" small or subtle features from the dataset that are of interest to the study. This was made apparent during the initial generation of the amplitude slice-maps using standard reduction and interpolation procedures, which showed only a few of the postholes. After excavation revealed numerous others, getting them to appear in the GPR slice-maps was achieved by using a higher number of data samples per meter when gridding the data (about four times the default on most software programs), and setting higher statistical thresholds for displaying the variations in amplitudes in the maps. Furthermore, many of the features in Room 28 were interpreted from a combined analysis of the slice-maps and reflection profiles, which are critical in showing the vertical geometry of reflections that might relate to features of cultural interest (Conyers 2012). This type of iterative manual interpretation, particularly without the benefit of excavation data, can add considerable processing time to a project and requires familiarity with GPR data collection and processing.
Secondly, using the 400 MHz antenna allowed an impressive three meters of depth penetration in these sediments, but came with a tradeoff of small-feature resolution. In addition to the six floor postholes and one wall post that could be measured with GPR, an additional 20 postholes were uncovered in Room 28 (19 incorporated into walls and 1 in the floor described above) that were either too small (less than 10 cm in diameter) to resolve using this antenna frequency or surrounded by walls that made them indistinguishable from the wall material. Nineteen had no lining; one had a partial sandstone lining. Using a higher frequency antenna could potentially resolve these features, but would come at the expense of overall depth penetration. This trade-off of depth penetration to feature resolution may limit the interpretability of a survey, depending on the types of research questions being asked.

Finally, the physically restrictive space of Room 28 constrained the data collection strategy. Equipment size and configuration (i.e., attaching a survey wheel, as was done in this survey), and need to maneuver within the room put practical constraints on the number of profiles that could be collected, as well as the profiling direction. For example, collecting transects that extended the width of the room (2.75 meters wide) was not practical with an attached survey wheel, and so collection was limited to transects that covered the length of the room (about 8 meters). With such a small area, having only one direction of transects potentially limits the type of analysis that can be done, depending on the orientation of buried features or stratigraphic layers. In this study, it is possible that more features could have been identified at the outset with data from two surveying directions. For future studies, modifying the equipment (making the attached
survey wheel smaller and more compact) will help achieve the goal of collecting data when the transect length is only a few meters.

Even with these challenges, a number of valuable insights were obtained from this survey. Postholes were the deepest and smallest features mapped in this survey. They are of particular interest because they served as important architectural supports in this room. Those postholes that contained sandstone linings showed up particularly well in the GPR images, and a few were predicted prior to excavation. When numerous other posts were revealed during excavation, adjusting the data processing using the procedures described above helped to image those posts as well. In total, six floor postholes and one wall post could be imaged in the GPR maps at a depth of just over two meters. Given the importance of posts and postholes in the construction and architectural styles of pueblos, refining the ways these features are imaged would have considerable benefit for future studies where excavation data are not available. This can be accomplished by conducting more GPR surveys in both "control" areas (rooms that have been artificially constructed to mimic an actual pueblo room) and in unexcavated rooms to further characterize the geophysical signature of such features. Given the promise of imaging such features from this study, this is a direction for future research we plan to pursue.

In addition to postholes, the identification of entryways has promise for future GPR surveys in these contexts. The entryways in Room 28 are located in the north and south walls leading into two adjacent rooms and a plaza, respectively. Even though these doorways were surrounded with mixed backfill sediments, the stratigraphic "breaks" associated with these entryways are clearly visible in the GPR reflection profiles and as areas of higher amplitude reflections in the slice-maps. We exposed and confirmed two of
these doorways during the 2013 excavation. We could not expose the third due to concern over wall collapse, but the 1896 photographs and published descriptions confirm its location. The GPR signatures from these entryways may therefore serve as a model for identifying buried doorways in other rooms, which may lend insight into how rooms were modified and made more or less restrictive.

Finally, this study has shown the promise of mapping burned sediments within rooms, even in a disturbed context. Burned materials are highly reflective in a primarily sandy matrix, and show up quite well in the GPR data. This has promising implications for other rooms within Pueblo Bonito, or other sites in Chaco, that have not been previously excavated. Locating undisturbed burned layers in other rooms and then relating the depth of those layers to known architectural phases or other subsurface information can potentially be a way to date the relative use and abandonment of particular rooms. Similar to identifying buried doorways, mapping burned layers may be a way to study the change in space and rebuilding phases within a larger site. Archaeologists interested in targeting burned material for dating may also use this technique to identify locations and depths for potential excavations.

**Conclusions**

The GPR method was successful at mapping three primary categories of features within Room 28: posts/postholes, entryways, and burned layers/sediments. When interpreted in the framework of previous research at Pueblo Bonito, these features are clear markers of specific construction and abandonment events within this room. At least some of the postholes, which were the deepest features located, indicate the initial
foundation and beginning construction of this room. They are particularly reflective in the GPR maps when they are lined with rock. Similarly, burned sediments showed up well with the GPR mapping. In an undisturbed context, these burned layers could have been analyzed for their depth and distribution to provide information on burning events within a room. Finally, buried entryways in both the north and south walls were seen as peripheral reflections from the transmission of radar energy collected adjacent to the walls. By locating such entryways, it becomes possible to interpret which rooms were connected, which were not, and begin to analyze what that means in terms of access points and connectivity within the larger pueblo.

The utility of GPR within archaeology has been well-established, and its historical use as a prospection tool will continue to have great importance in archaeological endeavors. However, it is becoming more and more common for archaeologists to use GPR in a way that directly informs on topics of cultural interest. This study has demonstrated both the benefits and challenges of using GPR as a micro-scale mapping method to identify features within an interior pueblo room that can be used to understand the use and changing function of that room. Ideally, this information can be put into a wider site context to study how specific rooms were used, modified, and abandoned over time. By directly comparing the GPR data with the excavation results (Figure 2.7), we were able to assess how GPR mapped specific features within this room and identify the variables that made certain features resolvable in this context. This project is an important step towards removing ambiguity regarding how small features appear in GPR images, and additional future surveys should help to further clarify such geophysical signatures. Using the information generated from this study, we are in a better position to identify
similar features in other rooms and interpret them in a way that addresses research
questions. This type of approach has applicability beyond Pueblo Bonito or even Chaco
Canyon, and can be used in many other interior room surveys throughout the American
Southwest.
Chapter 3 - A Remote Sensing Approach to Studying Land Use Change in Chaco Canyon

This chapter is adapted from a contributed chapter in the 2017 volume edited by Duncan McKinnon and Bryan Haley, Archaeological Remote Sensing in North America: Innovative Techniques for Anthropological Applications.

Introduction

The ways in which humans use and modify their landscapes often reflects larger social, economic, and political changes within a societal system. In North America in general, and the American Southwest in particular, land modification related to prehistoric land use has reemerged as a topic of interest because of its hypothesized long-term impact on ecosystem structure and implications for social complexity (Dean 1992; Van West 2011). Yet locating and characterizing the spatio-temporal patterns associated with prehistoric land use is often a major methodological challenge. Unless the land use activity included substantial architecture, many features related to land use in the Southwest can be easily buried over time, or so subtle that they are hard to recognize as such. Furthermore, detecting change in land use, or how a possible landscape was modified over time, can be even more challenging.

Remote sensing, especially when combined with other geospatial methods, offers a means of detecting land use patterns that may otherwise be excluded from the cultural interpretations of an area. While remote sensing has been used in American archaeology for many decades, the ways in which these methods are applied to problems, and the interpretations that are now possible from them, continues to expand and evolve.
This chapter presents a case study on using remote sensing methods to distinguish complicated sets of localized land use patterns in Chaco Canyon, New Mexico.  

Prehistoric land use in Chaco is a complex topic with differing interpretations, and this is exemplified by a feature often referred to as the “Chetro Ketl field” (Figure 3.1). Using a time-series of historic aerial photographs and GPR, complex configurations of features buried below the visible part of the Chetro Ketl field were identified. While the function of these buried features is unclear, the results from this study do suggest that this overall area was rebuilt at some point, possibly reflecting an economic or social shift in Chacoan society. Furthermore, it is likely that other extensive buried complexes of features that are not evident on the surface exist in additional parts of the canyon and beyond. The remote sensing approach developed for this specific study can provide a non-destructive strategy for locating them, helping to offer new insights about the "invisible" Southwestern landscape.
Figure 3.1: Chetro Ketl field complex, located southeast of the Chetro Ketl great house in Chaco Canyon.

Background

Chaco Canyon, located in northwestern New Mexico in the American Southwest (see Figure 1.1), hosted one of the largest and most socially complex societies of the Ancestral Puebloan world. Flourishing from about A.D. 850-1150, Chaco is best known for its monumental, multi-story great houses, numerous great kivas, a highly formalized masonry building style, elaborate ceramic designs, and imported exotic materials (Judge 1991:24). Today, Chaco Canyon is administered by the National Park Service (NPS). Chaco’s great houses are often cited as some of the clearest examples of emergent social complexity in prehispanic North America, and therefore have been researched extensively (e.g., see Neitzel 2003; Lekson 2007). Far less attention has historically been given to the land in-between these great houses, leading to ambiguity about what types of
land modification occurred and how that relates to land use activities. The research that has been done has led to conflicting interpretations regarding land use, even when the same evidence is used.

For example, some researchers have argued that Chaco’s landscape was one that served a primarily economic function by being modified to control the flow of water onto agricultural fields (Sebastian 1992; Vivian 1970, 1974, 1990; Vivian, et al. 2006). The example most often cited as an agricultural field is often referred to as the “Chetro Ketl field.” This area is a large (roughly two hectares), rectangular-shaped feature a few hundred meters southeast of the Chetro Ketl great house (Figure 3.1). In addition to the overall differences in soil coloration and vegetation, a faint interior grid pattern is visible in most aerial photos. Gridded fields, in which a larger area is sub-divided into smaller plots, are well-documented features in the agricultural economies of many protohistoric and historic Pueblo societies (Anschuetz 2006; Dominguez 2002; Maxwell and Anschuetz 1992; Wills, et al. 1990). It has been hypothesized that if one of these gridded fields exist in Chaco, then others likely do as well, and are simply buried due to alluvial deposition (Vivian, et al. 2006).

Not all researchers, however, agree with the “agricultural landscape” interpretation. A common alternative explanation of land modification at Chaco relates to what has been called a sacred or ritual landscape (Van Dyke 2007). This perspective explains many elements of the built environment as establishing sacred connections to a worldview, promoting ceremonial activities, or reinforcing social ideology (Sofaer 2007; Stein, et al. 2007). For example, under this explanation, the “Chetro Ketl field” is
interpreted as a series of ball courts or areas for ceremonial performances (Stein, et al. 2007:211).

Both of these examples of interpreting prehistoric land use at Chaco include evidence from the same feature (the Chetro Ketl field), making it one of the most ambiguous instances of land modification in the canyon. Each interpretation of this feature carries vastly different implications for Chaco's societal structure, including agricultural infrastructure and innovation, economic intensification, resource management, and ritual investment. Therefore, refining how the Chetro Ketl field area is interpreted directly affects our understanding of the potential causal relationships between Chacoan society and the resulting land modification.

One major reason the Chetro Ketl field area has been so difficult to interpret is because no obvious comparable features in Chaco have been located (Love 1980; Morain, et al. 1981; Stein, et al. 2007; Stein and Fowler 1996). Concerted efforts were made in the 1970s and 80s, when a number of remote sensing technologies were applied in Chaco. Many of these experiments, most notably those using aerial photography and photogrammetry, were pivotal in Chacoan archaeology, helping to locate and define features that were imperceptible from the ground surface. In addition to aerial techniques, a number of geophysical methods, including GPR and magnetometry, were used in an attempt to map buried features in Chaco. These efforts, which included experiments at Pueblo Bonito and the Chetro Ketl field area, were pioneering as some of the first applications of geophysics in American archaeology (e.g., see Lyons and Avery 1977; Vickers, et al. 1976). Despite some promising results, most of these geophysical efforts were inconclusive. However, it is noteworthy that rather than abandon the promise of
such methods, researchers framed the problem in terms of future technological development, hypothesizing that "...refinements in...instrumentation and data interpretation programs may allow detection of subtle soil density changes typical [of these features]" (Loose and Lyons 1976:145).

Forty years later, this statement seems almost prophetic. Geophysical methods that were once experimental have become standard practice in many types of archaeological fieldwork, including in the American Southwest. Advancements in technology and computing power mean large areas can be covered quickly, and data can be processed into images that are readily interpretable (Conyers 2013). Re-focusing remote sensing efforts in Chaco not only carries on the important legacy of such work started in the 1970s, it also offers a way to study land use in Chaco while adhering to the NPS mission of preservation.

As shown in the following sections, remote sensing and geospatial methods offer a logistical solution to studying land use patterns in Chaco non-invasively, while also generating data about the Chetro Ketl field area that are not observable from any other source. The maps produced from this study are both independent of previous archaeological studies and can be used to guide and complement any future excavations here.

**Methods and Approach**

In this project, GPR was used as the primary method for mapping buried features within the Chetro Ketl field area. Using GPR in conjunction with other geospatial methods helped contextualize the GPR results with the surrounding landscape. These
methods included a time-series of historic aerial photos that were used to document and define the visible surface patterns in this area, a real time kinematic global navigation satellite system (RTK GNSS) to accurately relate the GPR survey areas to the aerial photos, and integration into a GIS environment to allow a platform for analysis and interpretations.

Chaco Canyon has been photographed for decades, and a multitude of aerial photos dating back to the 1920s exist for the area. While these photos have varying degrees of resolution, the time-depth offered by these photos is an excellent way to account for some of the landscape changes of the past century (Jensen 2005). For the Chetro Ketl field area, historic aerial photos are the only way to observe features that existed prior to NPS building a modern road directly through the field area (Figure 3.1).

Using six sets of photographs ranging in dates from 1935 to 2011, interior plot borders within the Chetro Ketl field area were digitized and recorded. Only those plot borders that were clearly visible were recorded, without inferring borders that might have created a full grid. All photos used for this analysis are housed at the Earth Data Analysis Center (EDAC) and online GIS repository at the University of New Mexico, and each was georeferenced and coregistered using the most recent aerial photos (1 meter resolution) as a reference frame. Using this strategy, numerous plot borders were recorded that are not apparent on contemporary imagery, including some that existed prior to the modern road being built. The final product of this effort was a composite image showing all borders visible on the surface over the course of nearly a century (Figure 3.2).
Figure 3.2: Close-up of the Chetro Ketl field complex. The linear features visible in a time series of historical aerial photos have been digitized with black lines. The GPR survey grids (white rectangles) are also noted.

Once the aerial photo analysis was complete, sample areas within the field area were selected for GPR survey. While the overall field area is easily visible in aerial photos, it is almost imperceptible on the ground, a problem noted by geophysical archaeologists in the 1970s as well (Loose and Lyons 1976:134-137). To overcome this visibility problem, all GPR grids were selected for placement based on the aerial photos in a GIS environment. These survey areas were then made into rectilinear grids and sized to maximize the amount of ground covered while also limiting the amount of vegetation included in a survey area. These survey grids were then input as a shapefile into the RTK GNSS to stake out, thereby allowing specific areas of interest to be targeted and
eliminating any guesswork from survey location. Perhaps most importantly, this strategy easily allowed the GPR grids to be oriented so they were offset from the linear plots visible in aerial photographs (Figure 3.2). This helped avoid collecting transects parallel to the linear plots, which runs the risk of being removed as horizontal banding during post-processing (Conyers 2013).

To minimize the impact on vegetation within the park and maximize available field time, survey areas were chosen in locations that were generally free of large bushes and other major surface obstacles. The majority of GPR grids were placed over the visible grid borders with the goal of better defining the field area and testing for buried features. Two GPR grids were placed outside of these visible grid borders to test for features outside of the grid area (Figure 3.2).

The GPR method was selected for this study both because of previous contemporary successes using it within the canyon (e.g., see Sturm and Crown 2015), and based on the need for high-resolution maps that could be analyzed at various depths in the ground. Over the course of three field seasons, GPR data were collected with a GSSI SIR 3000 controller using 400 MHz antennas. All data collected within the field area were collected in rectilinear grids using a 50 cm transect spacing. The data were processed to generate both reflection profiles and amplitude slice-maps using the programs GPRViewer+, GPR Process, and GPR-SLICE. Various standard processing techniques were utilized in an iterative process to generate interpretable maps, including background filtering, low-pass filtering (3 x 3), and utilizing a high data sample rate to generate relatively thin slice-maps (between 2-3 nanoseconds) (Conyers 2013; Goodman and Piro 2013). To convert time measurements into actual depth, a velocity analysis was
performed (Conyers 2013; Conyers and Lucius 1996) and resulted in an average relative dielectric permittivity (RDP) of 5.2.

A total of 15 grids have been collected thus far. All of the amplitude slice-maps that were generated for each survey area were converted to raster images and georectified to the aerial photos in a GIS environment. Features visible in the slice-maps were then digitized to compare to the plot borders identified in the historic aerial photo analysis. This allowed a platform for visualizing how subsurface features related to surface features.

Results

A number of shallowly buried, long linear features were identified in many of the GPR slice-maps (Figure 3.3). Some of these linear features have a low reflectivity and appear as only subtle reflections in the amplitude slice-maps. Still, the linear nature of these reflections is unmistakable (Figure 3.3). To determine possible association, the linear features identified in the slice-maps were analyzed according to depth after being converted from time measurements. While all the identified linear features appear shallow (occurring within the first 50 cm of subsurface), the depth analysis showed that some linear features consistently occurred below others. In total, three distinct categories of linear features were identified and interpreted from the GPR maps: 1) the grid borders visible in aerial photographs, occurring at the surface and extending to about 8 cm in depth (Figure 3.4b); 2) linear features not visible in aerial photographs, but oriented in the same direction as the surface grid pattern. These were often found within the grid borders visible in aerial photos, and were mapped primarily at a depth of 10-20 cm (Figure 3.4c);
and 3) linear features neither visible in aerial photographs nor oriented in the same direction as the surface grid borders. These features were mapped primarily at depths ranging from about 15-50 cm (Figure 3.4d). In addition to the linear features, a number of shallow, basin-like circular features were mapped that also appear primarily at depths from about 10-50 cm (Figure 3.4d). All of these circular features appear in the southern part of the field area, and none appear to intersect the deeper linear features. These basins range in size from about 2-5 meters in diameter, and the majority appear to extend to no more than 90 cm deep.

![Diagram of buried linear and circular features]

Figure 3.3: Three amplitude slice-maps from three distinct grids in the southern part of the field complex. The reflections from several buried linear features and two circular features are apparent in the grids, and at least one linear feature extends through all three grids. These linear features are buried below the grid pattern evident in aerial photos, suggesting that they are associated with an earlier feature. These slice-maps represent a depth of approximately 12-20 cm.
Figure 3.4: Chetro Ketl field complex showing (a) linear features identified from a time series of historical aerial photos; (b) linear features that were mapped with GPR and are visible in the aerial photos; (c) linear features that were mapped with GPR but are not visible in the aerial photos yet are oriented in the same direction; and (d) linear features mapped with GPR that are not visible in the aerial photos or oriented in the same direction. Also shown are the GPR survey grids and a number of small circular features that were mapped with GPR.

Discussion

The results from this study show that there are configurations of buried features in the Chetro Ketl field area that are distinct from the grid patterns apparent on the present ground surface (Figure 3.5). The linear features visible on the surface are oriented approximately 45 degrees from the buried linear features, and are spaced about 20 meters apart at their widest part, which is twice the distance of the buried linear features. On the south end of the field area, the buried linear features become narrower, and cross each other in at least one place (Figure 3.5). The southern part of the Chetro Ketl field area is
also where the buried circular features are located. None of these circular features overlap with or intersect the deeper linear features, suggesting they were either already there, subsequently built within, or built in conjunction with, the original linear features. While the specific function of these circular features is currently unknown, their presence and patterning with the deeper linear features suggests they may be part of the same configuration.

Figure 3.5: Chetro Ketl field complex showing the hypothesized relative chronological history of this area. The deeper linear features likely represent an earlier configuration. At some point, new linear features were built, rotated, and superimposed directly on top of the earlier configuration. All that is visible in aerial photos today is the final grid pattern.

Excavation records from testing within the Chetro Ketl field during the 1970s offer some clues on the nature of these buried linear features. These records show the presence of earthen berms interspersed with sand and clay layers throughout the Chetro
Ketl field area (Loose and Lyons 1976). In the GPR reflection profiles, these linear features are often difficult to distinguish from their surrounding sediments, but most appear as subtly reflective vertical “breaks” in the subsurface. This suggests that if these are earthen berms, then they may have been constructed more like a wall with vertical edges than a mounded berm with sloped sides.

Taken together, the information derived from the GPR analysis, historic aerial photo analysis, and GIS integration, appear to represent a temporal series of building episodes. The earliest (deepest) evident feature consisted of long, linear features oriented northwest to southeast and spaced approximately 10 meters apart, with perpendicular linear features spaced approximately every 55 meters. These linear features become narrower and less uniform in the southern part of the field complex, crossing in at least one place. Also possibly associated with this earlier configuration are the multiple circular basin features.

At some point, new linear features were built in this area and superimposed directly on top of the earlier system. The entire layout appears to have been rotated about 45 degrees from its original configuration and structured to form grids that measure approximately 23 meters east-west and 14 meters north-south. These grids are remarkably uniform in both shape and size. It is also possible that intermediate features were built during the reconstruction of this area, as evidenced by other partial linear features buried within, and oriented to, the surface grids. All that remains visible in aerial photos, however, is the final gridded pattern (Figure 3.5).
Conclusions

The Chetro Ketl field area is one of the most ambiguous examples of land modification in Chaco Canyon because of its seemingly unique presence. The grid pattern visible on the surface of this area has been interpreted to represent very different land use functions, from a gridded agricultural field to ceremonial performance areas. None of these interpretations, however, has been conclusively linked to its functional correlate. The results from this study have shown that what is visible on the surface is actually only one component of the Chetro Ketl field area, and this may be one of the reasons the Chetro Ketl field has been so difficult to interpret. Therefore, while this study does not necessarily establish its function, it does suggest that there is a significant component of this feature currently being excluded from its interpretation. It is possible that no part of this feature would be visible today if it had not undergone extensive remodeling at some point in its history. This suggests the tantalizing possibility that other land use patterns exist throughout the canyon, but remain invisible from the surface due to sediment deposition. More work needs to be done to expand our understanding of this feature and determine if it fits within a broader system of land use in Chaco, or represents a localized palimpsest of prehistoric activity.

Determining that an extensive pattern of buried features exists below the gridded pattern seen in aerial photos could not have been accomplished without GPR survey. The field area and its gridded plots are imperceptible on the ground, and none of the buried features located are identifiable in aerial photos. The ability to analyze depth from the GPR data meant it was possible to recognize the buried features as likely associated with each other. Still, using GPR in combination with other geospatial methods, including the
time-series of historic aerial photos, a sub-centimeter GPS (RTK GNSS), and GIS, truly allowed the most robust analyses. By accurately integrating the information derived from multiple mapping platforms, it was possible to recognize this episode of land modification and hypothesize a relative chronological sequence of building activity for this area.

In addition, these buried features are so expansive that they would not be detectable with excavation without stripping nearly two hectares of ground surface. Excavations in the 1970s were successful at revealing some of the complex stratigraphy in this area, but the excavators had no way of knowing that some of what they observed related to a different configuration of features, let alone the size, orientation, or expanse of that original complex. This study therefore stands in stark contrast to misconceptions that remote sensing is an initial estimate of features in an area that then need to be refined through excavation. Rather, this study shows that remote sensing can be used as a stand-alone approach that generates new data that can be used directly to test an archaeological question in ways that are not observable from other sources. Should excavation occur here in the future, these maps can now effectively guide the placement of those excavations in ways that are more thoughtful and efficient.

The use of remote sensing in American archaeology is not new, but the ways in which archaeologists apply these methods and integrate them with other technologies will continue to evolve. New questions and new problems will require new approaches and solutions. In a place like a National Park, where preservation and protection of cultural resources is the Park’s primary mission, the need for non-invasive or minimally-invasive archaeology will continue to grow in importance. The use of remote sensing not only
helps overcome logistical problems with studying certain archaeological sites, it also expands the types of questions that can be asked. Given that the alternative might be to avoid working in such areas altogether, the use of remote sensing technology can only be considered beneficial for archaeology.
Chapter 4 - Using Ground-penetrating Radar to Re-evaluate the Chetro Ketl Field Area in Chaco Canyon

This chapter is adapted from a 2016 article that appears in Journal of Archaeological Science: Reports 7:238-246.

Introduction

Chaco Canyon, New Mexico, was the location of one of the largest and most socially complex areas of the Ancestral Puebloan world from about A.D. 850-1150 (Figure 4.1). Explanations of Chaco's complexity often include local crop production and water management, and substantial research efforts have addressed the paleoclimatic and geologic conditions that affected agriculture in Chaco (Dean 1992; Dorshow 2012; Force, et al. 2002; Sebastian 1991; Vivian 1990, 1991; Wills and Dorshow 2012). However, locating definitive features related to agriculture during the Bonito Phase (A.D. 850-1150), and especially agricultural fields, has been extremely difficult.
Figure 4.1: Chaco Culture National Historical Park, located in northwestern New Mexico. Major sites and features are noted, as well as the focus of this study, the Chetro Ketl field area.

Currently, the only location interpreted as a prehistoric agricultural field on the basis of visible patterns is the “Chetro Ketl field,” a large rectangular area a few hundred meters southeast of the Chetro Ketl great house (Figure 4.2). In addition to variability in soil coloration, a faint interior grid pattern is visible in most aerial imagery. Gridded fields, in which a larger area is sub-divided into smaller plots, are well-documented features in the agricultural economies of many protohistoric and historic Pueblo societies (Dominguez 2002; Maxwell and Anschuetz 1992; Wills, et al. 1990). By analogy to these ethnographic field systems, many researchers have interpreted the Chetro Ketl area as a similar agricultural field system (Sebastian 1992; Vivian 1970, 1990; Vivian, et al. 2006). Excavations by the National Park Service in the early 1970s confirmed the presence of
low sandy berms within the gridded area, and researchers view these as borders for
cultivation plots (Loose and Lyons 1976a). Since then, the "agricultural field" appellation
has been central to various models for agricultural production at Chaco during the Bonito
Phase, including arguments for economic intensification (e.g., see Sebastian 1988, 1992;
Vivian 1990).

Figure 4.2: NAIP (2014) imagery showing the Chetro Ketl great house and the field
area southeast of Chetro Ketl.

A number of researchers, however, have been skeptical that the Chetro Ketl field
area was in fact an agricultural feature (Love 1980; Morain, et al. 1981; Stein, et al. 2007;
Stein and Fowler 1996). Part of the uncertainty surrounding the function of this gridded
area is that no similar features have been identified in Chaco Canyon, despite decades of
intensive remote sensing and archaeological research. To date, several alternative
explanations for this gridded area have been proposed, from ceremonial performance
areas (Stein, et al. 2007:210), to the foundation of a great house that was never built (Stein and Fowler 1996:120), to frog ponds (Love 1980:345).

Recently, new ground-penetrating radar (GPR) surveys were conducted throughout the Chetro Ketl field area with the goal of clarifying some of the questions about the intended purpose of land modification that produced the gridded patterns visible only on aerial imagery. The results from these GPR surveys show that there is an extremely complicated series of buried features in this area, most notably linear patterns that are reminiscent of the grids visible on the surface, but are oriented differently. Because these features occur below the visible grids, it is possible that the area is a palimpsest of prehistoric land use changes, rather than a single episode of modification. These data do not necessarily confirm an agricultural role, but they do suggest that extensive buried complexes of features that are not evident on the surface may occur in other parts of the canyon. GPR survey, especially when combined with historic aerial photo analysis, can provide a non-destructive, cost-efficient approach to locating them.

Background

According to Richard Loose and Thomas Lyons (1976b:136), the Chetro Ketl complex was first observed in aerial photographs taken by Charles Lindbergh in 1929. However, R. Gwinn Vivian (1970, 1974, 1990, 1991) was the first researcher to investigate this area from the perspective that it contained likely agricultural fields. The area is located less than 300 meters southeast of the Chetro Ketl great house, and has an overall rectangular shape with markedly different soil coloration and vegetation patterns than the land surrounding it and a series of smaller rectangular features located within the
larger rectangular area that form a distinct gridded pattern (Figure 4.3). These grid lines are easily distinguishable from the air but imperceptible on the ground. Estimates of the field area have varied from about 1.8 hectares (Loose and Lyons 1976a) to over 4 hectares (Vivian 1974), and the number of estimated grid plots ranges from 42 (Loose and Lyons 1976a:134) to 160 (Vivian 1974:105). Consequently, while the overall area encompassed by grids can be clearly seen in aerial photographs, the actual extent and structure of the complex has not been established (Figure 4.4).

Figure 4.3: The grid pattern associated with the “Chetro Ketl field” is clearly seen in historic aerial photos, and was digitized and georeferenced for this study. Photo credit: Aerial view of Chetro Ketl, UNM Field School Photos, Chaco Canyon (Catalogue No. 88.43.411), Maxwell Museum of Anthropology, University of New Mexico.
Figure 4.4: Schematic drawing of the Chetro Ketl field complex by NPS (adapted from Loose and Lyons 1976a: Figure 7). Some potential features associated with this field complex are hypothesized or unclear, as noted with question marks.

In the early 1970s, the National Park Service Division of Remote Sensing used the Chetro Ketl field area to evaluate a number of emerging remote sensing technologies, including both aerial and ground-based methods (Loose and Lyons 1976a:133). These experiments were pioneering as some of the first problem-oriented applications of remote sensing in American archaeology. Methods including thermal aerial photography, magnetometry, and GPR were all tested in the Chetro Ketl field area. While all showed promise for future studies, none were deemed particularly successful at mapping the extent of the field or its buried components (Loose and Lyons 1976a; Vickers, et al. 1976).
Following the remote sensing experiments, seven trenches totaling 211 meters in combined length were excavated in various locations throughout the field complex (Figure 4.5). These trenches revealed a flat, level buried surface with earthen berms comprised of interspersed layers of sand and clay sediments (Figure 4.5). Based on this evidence, it was hypothesized that the area had been purposefully engineered to control water input from both the side canyon cliffs and overbank flooding from the Chaco Wash (Loose and Lyons 1976a). Researchers also suggested that the earthen berms were configured in a grid pattern to maximize the amount of water retained in each field plot (Loose and Lyons 1976a:142). At least one trench (Trench 6) was described in Richard Loose's 1974 field notes as containing a possible irrigation ditch, while part of a small pile of masonry and sandstone was described in another (Trench 5). In his field notes, Loose hypothesized that this concentration of masonry and sandstone might relate to a gate or water control feature, or a "patch" to mend a partially destroyed earthen berm (Richard Loose, 1974 unpublished field notes, Chaco Collections Archives, Albuquerque).
Figure 4.5: Locations of the seven test trenches excavated by NPS in 1974, georeferenced to 2014 NAIP imagery (top image), and a profile drawing of Trench 3 as drawn by NPS (bottom image, adapted from Loose and Lyons 1976:141).

While at the time the results from these excavations seemed to support the interpretation of this area as an agricultural field, those same data would later be questioned as evidence of agricultural activity. Love (1980:345) analyzed the geology of
the test trenches and noted the unsuitable nature of the clay substrate for cultivation, as well as an absence of soil churning that would indicate plant growth. In his description of Trench 6, Loose also noted that a possible alternative explanation for the irrigation ditch was a historic road cut, and this feature appears to have been omitted from the 1976 drawing of the field complex (Figure 4.4). Aerial images show that Trench 6 likely cuts across a historic road (Figure 4.5). The masonry/rubble pile described in Trench 5 may correspond to a small masonry structure that is partially visible on the modern surface and documented in recent site assessments of this area. The actual function of this small structure, however, is still unclear. Compounding the ambiguity of the evidence at the Chetro Ketl field area is the lack of other similar features in the canyon that could be used for comparison (Morain, et al. 1981). The seemingly unique structure of this feature has led several researchers to postulate alternative explanations for its function. Stein, et al. (2007:210) reviewed several alternatives to agricultural production that have been proposed, including adobe mixing areas, ceremonial performance areas, ball courts, and frog ponds.

In contrast to the experimental remote sensing work in the Chetro Ketl area in the 1970s, methods such as GPR are now valuable and routine in archaeological fieldwork (Conyers 2010; Conyers and Leckebusch 2010; Kvamme 2008; Thompson, et al. 2011). Advancements in technology and computing power mean large areas can be covered efficiently, making GPR particularly well-suited for problems that require larger areas to be mapped and interpreted through their spatial layout and organization (Conyers 2009). In addition, because the GPR method measures depth, it is useful in areas with complex stratigraphy or with overlaying features. These data are commonly processed to generate
two-dimensional and three-dimensional renderings of reflection strengths, resulting in maps that are often powerful visualizations of archaeological features. The new application of GPR in the Chetro Ketl field area provides a dramatic improvement on previous remote sensing studies and offers new insights about the “invisible” Chaco landscape.

Methods

In addition to GPR survey, historic aerial photos were used both to select areas for GPR survey and to interpret the results. A real time kinematic (RTK) global navigation satellite system (GNSS) was used to maintain spatial control over the GPR collection areas. Each method and the overall data collection strategy is discussed below.

**Ground-penetrating Radar Survey**

The GPR data were collected with a GSSI SIR 3000 controller using 400 MHz antennas and an attached survey wheel. All data were collected in rectilinear grids using a 50 cm transect spacing and 40 samples per meter using a north-south transect profiling direction. The data were processed to generate both reflection profiles and amplitude slice-maps using the programs *GPRViewer+* and *GPR-SLICE*.

Amplitude slice-maps refer to the visualization of changes in reflections across a given area and at various depths in the ground (Conyers 2013; Goodman and Piro 2013). These types of maps are generated through the comparison of reflected amplitudes recorded in vertical profiles. When many profiles are collected adjacent to each other in a
grid, the digital values of amplitude variations can be compared and spatially interpolated with the digital values of nearby profiles. This database can then be “sliced” horizontally and displayed to show the variation in reflection amplitudes at a sequence of depths in the ground. The result is a map that shows amplitudes in map view at a discreet depth. Often when this is done, changes in the ground related to disturbances such as archaeological or geological features can become visible, making many features visible to the human eye that may not otherwise be apparent (Figure 4.6).

For this study, the amplitude slice-maps were produced using background filtering, low-pass filtering (3x3) and a high data sample rate. Each slice-map was generated at a 2 nanosecond thickness using an inverse distance weighting spatial interpolation. To convert time measurements into depth, a velocity analysis was performed (Conyers 2013; Conyers and Lucius 1996) and resulted in an average relative dielectric permittivity (RDP) of 5.2, or approximately 13 centimeters per nanosecond in two-way travel time. A total of 15 grid areas ranging in size were collected over the course of three field seasons in 2014 and 2015.

**Historic Aerial Photo Analysis**

Historic aerial photo analysis was used to help record interior grid borders that are not obvious in modern imagery. Six sets of photographs ranging in dates from 1935 to 2011 were used, and only grid lines that were clearly visible in photographs were digitized and recorded, without inferring borders that may have created a full plot. All photo frames are housed at the Earth Data Analysis Center (EDAC) at the University of New Mexico and on the state of New Mexico’s online GIS repository. Each photograph
was georeferenced and coregistered between years to provide a visual means of detecting landscape change over the past approximately 80 years. Using this approach, numerous grid borders were recorded that are not apparent on contemporary imagery, including some that existed prior to the modern road being built. The final product was a composite image showing all grid borders visible on the surface over the course of nearly a century (Figure 4.7a).

**RTK GNSS and Sampling Strategy**

Sample areas within the Chetro Ketl field area were selected for GPR survey after identifying the visible linear grid borders through the historic aerial photo analysis. Sections that included the edges of the field area and internal grid borders were a high priority in order to map the depth and spatial extent of any subsurface features. Six survey areas were initially chosen in a GIS environment, configured as rectilinear grids and then sized to maximize the amount of ground covered while also limiting the amount of surface interference (especially vegetation). Survey area coordinates were then input as a shapefile into the RTK GNSS to stake out, thereby allowing specific areas of interest to be targeted and eliminating any guess-work from survey location. This approach also allowed the GPR grids to be oriented so they were offset from the linear borders visible in aerial photographs to maximize target detection. This strategy also avoids collecting transects parallel to the target features, which runs the risk of being removed as horizontal banding during post-processing (Conyers 2013). After collecting and processing data from the six initial grids, an additional nine areas were selected for GPR
surveying using the same approach, for a total of 15 grids over the course of three field seasons in 2014 and 2015 (Figure 4.7a).

*GIS Integration and Geovisualization*

Amplitude slice-maps generated for each GPR survey area were converted to raster images and georectified into a GIS environment. Linear features visible in the GPR slice-maps were then digitized to compare to the grid lines identified in the historic aerial photo analysis. This created a platform from which to analyze and interpret the relationship of subsurface features to surface features. This process was completed using *ArcGIS 10.2, Global Mapper 15*, and *Surfer 11*.

*Results*

A number of subsurface linear features were identified in many of the GPR slice-maps. Figure 4.6 shows three contiguous amplitude slice-maps from GPR grids collected in the southern part of the field complex. Several distinct buried linear features were identified in these grids, and all are approximately 50 cm in width. The majority of these linear features are oriented in a northwest-southeast direction and parallel each other at a spacing of approximately 10 meters (though they become narrower in some places). One linear feature runs perpendicular to the others (Figure 4.6). In addition, at least two circular basin-like features are found in these slice-maps (Figure 4.6).
Figure 4.6: GPR amplitude slice-maps showing some of the buried linear features within the Chetro Kettel field area. These features are deeper than the grid pattern visible in aerial imagery and oriented in a different direction, suggesting they represent an older feature. Also noted are circular features that may be associated with this deeper configuration of features. These slice-maps represents a depth of approximately 12-20 cm below surface.

The linear features identified in all of the amplitude slice-maps were analyzed according to depth to determine possible association. While all the identified features are relatively shallow (occurring within the first 50 cm of subsurface), the depth analysis showed that certain linear features consistently occurred below others. Three distinct
categories of linear features were ultimately identified and interpreted from the GPR maps: 1) the grid borders visible in aerial photographs, occurring at the surface and extending to about 8 cm in depth (Figure 4.7b); 2) linear features not visible in aerial photographs, but oriented in the same direction as the surface grid borders. These were often found within the grids visible from aerial photos, and were mapped primarily at a depth of 10-20 cm (Figure 4.7c); and 3) linear features neither visible in aerial photographs nor oriented in the same direction as the surface grids. These features were mapped primarily at depths ranging from about 15-30 cm (Figure 4.7d). In addition to the linear features, a number of shallow, basin-like circular features were mapped that also begin primarily at depths from about 15-50 cm (Figures 4.6 and 4.7d). These circular features range in size from about 2-5 meters in diameter, and the majority appear to extend no further than about 90 cm in depth.
Figure 4.7: The Chetro Ketl field area included as part of this study showing A) Linear features identified from aerial imagery and confirmed as berms by the 1974 excavations; B) Linear features that were mapped both with GPR and visible in the aerial imagery (starting at the surface and extending to 8 cm in depth); C) Linear features mapped with GPR but not visible in the aerial imagery, but still oriented in the same direction (appearing at about 10-20 cm in depth); and D) Linear features mapped with GPR that are not visible in the aerial imagery nor oriented in the same direction (appearing at about 15-50 cm in depth). Also shown are the GPR survey grids and a number of small circular features that were mapped with GPR.

Discussion

The results from this study show that there are configurations of buried features in the Chetro Ketl field area that are distinct from the grid pattern apparent on the present ground surface (Figure 4.8). To better understand the nature of these buried features, the 1974 trench profile drawings were reviewed and compared to these new GPR data. Many of the trench profile drawings show earthen berms that extend up to the modern surface (see Figure 4.5), but one profile from Trench 4 shows an earthen berm that is located
about 20 cm below the surface (Loose and Lyons 1976a:141). This trench location was georeferenced into the GIS database generated from the aerial photo and GPR analysis, and was found to intersect one of the deeper linear features identified in the GPR amplitude slice-maps (Figure 4.9). In other words, it appears that the excavators recorded an earthen berm related to the deeper configuration of features, but did not associate it with an earlier feature. The excavators noted how difficult it was to see the earthen berms in the trench profiles, noting only subtle differences in sediment color and texture (Loose and Lyons 1976a:139). Slight variations in soil characteristics are difficult to perceive with the human eye, but are readily measurable with GPR. By sampling multiple areas within the field to map with GPR and then georectifying the features identified in these maps back to the aerial photos, the complexity of overlapping features becomes evident in ways that cannot be discerned in excavation trenches. Nonetheless, the trench data provide confirmation that these buried linear features are likely earthen berms, thereby independently validating the GPR maps.
Figure 4.8: The Chetro Ketl field area included as part of this study showing the four individual maps from Figure 4.7 combined into one map. The different orientation of the buried linear features becomes apparent when combined with the grid pattern visible in aerial imagery.

Figure 4.9: GPR amplitude slice-map showing buried linear features. The point of intersection between a GPR reflection profile (X1-X2) and excavation Trench 4 from 1974 (Y1-Y2) is labeled with a star. The excavators recorded a buried earthen berm in their trench profile, but did not identify it as associated with a different configuration of features.
Based on the depth information derived from the GPR analysis, the features mapped here appear to represent a temporal series of building episodes (Figure 4.10). The earliest evident features consisted of long, linear features (likely earthen berms) oriented northwest to southeast and spaced approximately 10 meters apart, with perpendicular berms spaced approximately every 55 meters. These berms become narrower and less uniform in the southern part of the field complex (Figure 4.10, black lines). It is difficult to ascertain the overall pattern of this earliest feature, but it is clear the layout of these features are not the same size, nor as consistent in shape, as the grids that are visible on the surface. Also possibly associated with this earlier configuration are the multiple circular features. All of these circular features were mapped in the southern part of the field area, and none overlap with or intersect the deepest earthen berms. This suggests that these circular features were either already there, subsequently built within, or built in conjunction with, the original berms. Therefore, while the specific function of the circular features is unknown, their presence and patterning suggest they may be related to the earlier earthen berms.

At some point, new earthen berms were built in this area and superimposed directly on top of the earlier system. These new berms were built on a northeast to southwest orientation (approximately 45 degrees from the buried berms), and configured to form grids that measure approximately 23 by 14 meters. These grids are remarkably uniform in both size and shape. It is also possible that intermediate features were built as well, as evidenced by other partial linear berms buried within, and oriented to, the surface.
grids (Figure 4.10, blue lines). All that remains visible in aerial imagery, however, is the final gridded pattern within the larger rectangular area (Figure 4.10, red lines).

Figure 4.10: Visualization of the hypothesized construction history of the Chetro Ketl field complex derived from GPR survey and aerial photo analysis. The earlier configuration, indicated by black lines (~15-50 cm depth), consists of long linear features, possibly earthen berms, oriented northwest-southeast, with a number of circular features possibly associated with it. This configuration was rebuilt and reoriented in a northeast-southwest direction (approximately 45 degrees), and the circular features were built over, resulting in the pattern preserved on the surface (represented by red lines). To reach its final form, there were likely transitional building episodes, resulting in remnant berms that were ultimately buried (represented by blue lines).

Conclusion

The Chetro Ketl field area is important because of its potential implications for a system of agricultural intensification at Chaco but it has not yet been conclusively linked
to farming. Interpreting this feature has been difficult partly because of a lack of other features in Chaco to use as comparison, leading to a variety of alternative explanations for this feature. While this study alone cannot determine the actual function of the Chetro Ketl field area, it has shown that what is visible on the surface is actually only one component of this feature. In contrast to explanations of the Chetro Ketl field area based only on its surface expression, this study suggests this area represents a palimpsest of land use activity. If other areas in the canyon had undergone similar extensive remodeling, they might also be visible on the surface today. In other words, similar subsurface features could potentially exist throughout Chaco Canyon, but remain invisible from the surface because they were not remodeled like the Chetro Ketl field area, or because they have been buried from soil/sediment deposition. The methods described in this paper, and particularly GPR survey, could be applied to other areas of the canyon to test for similar buried features to see if and how the Chetro Ketl field area fits into a broader system of land use at Chaco.

In addition, more work needs to be done in order to contextualize these findings and move towards a more robust interpretation of this area. It is clear from this study that the full spatial extent of the buried configuration of earthen berms has not been established. Additional GPR survey, especially in the southern and western parts of the field complex, should help clarify the full layout of these features. This study also focused solely on the interior gridded section of the Chetro Ketl field area. Future studies that expand beyond this gridded area to include other surrounding features will be critical for interpreting the Chetro Ketl field area as part of the broader Chaco landscape. Finally, to understand the chronological and functional correlates of these buried features, there
will need to be new fieldwork blending more expansive remote sensing investigations
with archaeological testing. GPR surveys can provide detailed maps of subsurface
features to effectively guide those future studies while minimizing the impact on this
complex area.
Chapter 5 - Evaluating the Gridded Agricultural Field Model in Chaco Canyon Using Geophysical Remote Sensing

*This chapter is adapted from a manuscript with the same title co-authored with Dr. W.H. Wills. It was accepted into the journal American Antiquity on November 8, 2019.*

**Introduction**

The emergence of social complexity during the Bonito Phase (ca. AD 850-1150) in Chaco Canyon, New Mexico (Figure 5.1), attested to by massive construction projects and possible hierarchical social structure, was supported by agricultural production, primarily maize (*Zea mays*) but also including squash (*Cucurbita pepo*), beans (*Phaseolus vulgaris*) and a wide range of non-domesticates that were likely cultivated or encouraged in field areas (Mathien 2005; Toll 2006; Toll et al. 1985; Windes 2015). However, the exact nature of agricultural strategies in Chaco during this time remains difficult to define; the location of agricultural fields within the canyon has been an especially vexing question.
R. Gwinn Vivian (1970, 1974, 1990:310, 1992:51; Vivian et al. 2006:50; Vivian and Watson 2015) recognized that Chaco farmers probably employed different types of agricultural fields according to local conditions but believed that the development of large gridded fields with associated irrigation ditches was critical to the evolution of social inequality during the Bonito Phase. In Vivian’s formulation, the construction and management of extensive formal field systems required the ability to coordinate large numbers of workers during brief but intensive periods of summer thunderstorms in order to allocate water effectively. Gridded fields were assumed to have been owned and controlled by great house residents, especially on the north side of the canyon, and great
house leaders used surpluses from these field systems to underwrite nascent social
differentiation between communities (Figure 5.2).

Gridded fields are common features in the agricultural economies of many
historical societies in the American Southwest, typically featuring large areas subdivided
into smaller plots to facilitate water distribution and crop growth (Dominguez 2002;
Maxwell and Anschuetz 1992). In southern Arizona, gridded fields occur along the
floodplains of major rivers by 1000 BC, and there is no doubt that for millennia farmers
in this region intensified agricultural production through the diversion of water in
carefully-maintained arrays of fields (Berlin et al. 1990; Fish and Fish 1992; Schaafsma
and Briggs 2007). In contrast, gridded field systems are rare in the archaeological record
of the northern US Southwest and especially the Colorado Plateau. In Chaco Canyon, the
only clearly visible example of a gridded feature (Figure 5.3), is found southeast of the
Chetro Ketl great house (Loose and Lyons 1976a; Love 1980; Sturm 2016; Wills 2017).
Models that show gridded fields throughout Chaco Canyon (e.g., Vivian et al. 2006) rely
on features such as masonry head gates and associated ditches as proxies for fields rather
than physical evidence for the presence of agricultural plots.
Figure 5.2: Schematic drawing of a gridded field system in Chaco, which is based on observable grid patterns near the Chetro Ketl great house. This field pattern is hypothesized to exist throughout the canyon floor, particularly on the north side, encompassing an area of approximately 900 acres of valley floor. Images adapted from Vivian 1990: Figure 8.38 and Vivian et al. 2006: Figure 2.2.
Since no areas in Chaco other than the floodplain southeast of Chetro Ketl exhibit visible patterns, it makes sense to ask whether geophysical remote sensing, including ground-penetrating radar (GPR) and magnetometry, might locate buried features in areas of predicted gridded fields that conform to a gridded array of field plots separated by irrigation ditches. In fact, researchers at the National Park Service’s (NPS) newly formed Division of Remote Sensing first asked this question in the 1970s. Created to assess the effectiveness of various remote sensing techniques for American archaeology, the Division of Remote Sensing systematically conducted some of the earliest remote sensing experiments in Chaco Canyon (Aikens 1980; Avery and Lyons 1978, 1981; Baker and Gumerman 1981; Camilli and Cordell 1983; Drager and Lyons 1985; Ebert and
Many of these efforts included the Chetro Ketl field area, involving some of the first applications of GPR and magnetometry in American archaeology (Loose and Lyons 1976a; Lyons et al. 1976; Vickers and Dolphin 1975; Vickers et al. 1976). Unfortunately, these pioneering efforts lacked the technological and computing power necessary to identify any subsurface features corresponding to the visible grids (Ebert and Lyons 1976; Lyons 1977; Lyons and Mathien 1980).

Archaeologists today routinely employ a range of non-destructive remote sensing techniques that have realized the original NPS Division of Remote Sensing goals of mapping complex and spatially expansive sites prior to expensive excavations (e.g., Burks and Cook 2011; Herrmann et al. 2014; Thompson 2014). In this study we offer a contribution to another of the Division of Remote Sensing’s major objectives, using remote sensing to evaluate specific hypotheses derived from prior archaeological research.

**Methods**

We selected three study areas previously identified as locations of gridded field systems: the Chetro Ketl complex, the area northwest of Casa Rinconada, and the area southeast of the Hungo Pavi great house (Figure 5.1). GPR was the primary geophysical method used, with magnetometry applied selectively as a comparative method. All GPR data were collected using a GSSI SIR-3000 data controller with 400 MHz and 270 MHz antennas. Data were collected in rectilinear grids and individual transects in select
locations of each study area that had been staked out with a real-time kinematic global navigation satellite system (RTK GNSS) to maintain sub-centimeter level spatial control. Data in grids were collected using 50 cm transect spacing and a sampling rate of 40 reflection traces per meter. The time window within which reflections were recorded ranged from 40-50 nanoseconds (ns), filtered between 135 MHz and 800 MHz depending on the antenna frequency being used. The data were processed to generate both reflection profiles and amplitude slice-maps using the programs GPRViewer+ and GPR-SLICE. To convert time measurements to depth, a velocity analysis was performed (Conyers 2013). This resulted in an average relative dielectric permittivity (RDP) ranging from 8.4 to 5.2, or approximately 10 to 13 cm/ns in two-way travel time.

Magnetometry was used as a secondary geophysical method in areas previously collected with GPR. The magnetic data were collected using a Bartington Grad601 fluxgate gradiometer, with transects collected using a 50 cm spacing and 8 samples per meter. The data were processed to generate magnetic gradient maps using the program Terrasurveyor.

The geophysical survey grids were placed throughout the selected study areas to evaluate as much area as possible while also avoiding surface obstacles such as heavy vegetation, which could not be removed within the national park. In all three study areas, additional grids were collected after the initial results from the surveys had been obtained. This iterative approach not only allowed us to adjust our collection strategy based on each survey’s results, it also generated a wealth of knowledge about the geophysical data collected during different seasons and over multiple years. The total surface area surveyed ranged from approximately 5,250 m² to 8,875 m² per study area.
All geophysical data were integrated into a GIS database to maintain spatial control over the survey areas and analyze the data in relation to the broader landscape. Because the majority of patterns being mapped are linear in nature, maintaining a high level of spatial control was critical for analyzing the layout and orientation of those features. Historic aerial photos housed at the University of New Mexico (UNM) and NPS Chaco Archives were utilized to assess land modifications from the historic period and aid in interpretations. Further information regarding data collection and processing procedures can be found in Sturm (2016).

The Study Areas and Survey Results

Chetro Ketl Field Area

The Chetro Ketl field area is defined by a large, rectangular area with noticeably different soil and vegetation properties than the land surrounding it, first photographed from the air by Charles Lindberg in 1929. A number of highly uniform grids are faintly apparent in modern aerial imagery (Figure 5.3). In addition to its notable grid pattern, several other visible features are often interpreted as part of the overall field system. These include long, narrow features that form a triangular shape west from the field area to the nearby Chaco Wash (Figure 5.3). The function of these features has been the subject of speculation, though they are most commonly explained as large earthen berms (Loose and Lyons 1976a; Stein et al. 2007:210). Other features considered standard components of a field system, such as headgates, are hypothesized to exist in relation to the field area but have not been definitively located.
Geophysical remote sensing by UNM researchers began in 2014 and initial results were reported by Sturm (2016). A total of 19 GPR grids, 19 GPR transects, and two magnetometry grids have been collected in this area (Figure 5.4). The first results from the GPR surveys showed a complex series of buried linear and circular features below the grid pattern visible on the ground surface. The overall layout of this buried pattern includes long linear features that are oriented northwest-southeast (approximately 45 degrees from the orientation of the surface pattern) with shorter linear features that intersect the others at varying angles (Figure 5.4). The overall pattern has some elements of a grid pattern but with far less uniformity than seen in the surface pattern. Most of the newly identified linear features are approximately 50 cm wide. Based on records from excavations conducted in this field area in the 1970s, it is likely that these buried linear features are small earthen berms (Loose and Lyons 1976a; Sturm 2016). In addition to these earthen berms, numerous circular features were identified in the GPR maps (Figure 5.4). These range in size from about 2-5 m, and extend no deeper than about 90 cm. Each exhibits a slight concavity in the reflection profiles, which gives them a basin-like appearance, though their function is unknown. In the magnetometry data, a number of very shallow linear features were mapped that show a similar orientation to the surface grid pattern but are not visible at the surface. Some of these very shallow linear features are also identifiable in the GPR (Figure 5.4). It may be that both the GPR and magnetic data are capturing transitional building episodes that culminated in the final grid pattern visible on the surface.

In addition to the geophysical grids collected within the main field area, 18 GPR transects were collected over the triangular area with the goal of determining whether
these long linear features were earthen berms. Fifteen of the GPR transects show distinct evidence of three linear features, possibly channels, seen as concave-shaped reflections and consistently measuring approximately three meters in width and approximately 80 cm in overall depth (Figure 5.5).

One GPR transect was collected over a hypothesized channel just north of the grid area that might have been the main channel diverting water from the mesa top onto the field area, according to reconstructions by Vivian (1990) and others (Loose and Lyons 1976a). This transect was inconclusive in confirming a channel but it is possible that a nearby historic road has obscured it, if it existed. However, the edges of other possible small channels were mapped in the northeastern-most grid but again, a nearby historic road has likely destroyed any additional sections of these possible channels. Another historic road is visible in the northwestern-most grid (Figure 5.4) and several trenches excavated in this area by NPS during the 1970s have been georeferenced and accounted for in the interpretations for this area (Figure 5.6).

In sum, the Chetro Ketl field area is the most complex of the three study areas and exhibits both lateral extensiveness and evidence of substantial remodeling (Figure 5.4). It is also clear we have not mapped its full extent. Additional future geophysical mapping should help further define this extensive complex.
Figure 5.4: The Chetro Ketl field study area, showing locations of the geophysical data collected as well as the interpretations made from the geophysical data analysis. The depths of features identified range from the ground surface to approximately 90 cm.
Figure 5.5: Reflection profiles collected in the triangular area of the Chetro Ketl field area showing the reflections from possible buried channels located throughout this area. These possible channels are visible in the reflection profiles from both the 400 MHz antenna (top) and 270 MHz antenna (bottom) and consistently measure approximately three meters across and extend approximately 80 cm below the ground surface.

Figure 5.6: Georeferenced locations of the 1970s trenches excavated in the Chetro Ketl Field Area.
Casa Rinconada Complex

The landscape northwest of Casa Rinconada is one of the few areas on the south side of the canyon that is explicitly described and drawn as having a gridded agricultural field system (Loose and Lyons 1976a; Vivian 1974). A small section of this gridded field area is shown on unpublished field maps (R. Gwinn Vivian, 1980 unpublished field notes, Chaco Collections Archives, Albuquerque, New Mexico). However, this gridded field has not been confirmed through testing and is not visible on the ground surface today. Furthermore, it has not been relocated or remapped since it was first recorded by Vivian. Vivian (1990:313; 2000:6) also described the area as having a canal irrigation system and he excavated several headgates in the area that had been remodeled while in use. Several excavated headgates are exposed on the surface but no canals are visible. Nine GPR grids, six GPR transects, and one magnetic grid were collected in the Casa Rinconada area (Figure 5.7). Several of the northernmost grids showed no evidence of archaeological features or only revealed features related to historic activity, including historic roads. This area was heavily utilized in the 20th century and it is likely that such activity has obscured or destroyed some land use features related to earlier Bonito Phase occupation. However, multiple features were identified in the southernmost geophysical grids and transects (closest to the landform on which Casa Rinconada sits) and are interpreted as possible features of archaeological interest.

High amplitude linear reflections in the GPR slice-maps represent possible edges of buried channels (Figures 5.8 and 5.9). Additionally, a number of lower amplitude linear features and circular features were mapped with GPR, particularly in Grids A-C (Figure 5.8). The differences in amplitude strength in this area are likely associated with
different materials or phenomena (Conyers 2013; Goodman and Piro 2013). The lower amplitude linear and circular features may have a higher clay content (thus attenuating the radar energy more quickly) or may be less substantially built and generating less physical contrast than other nearby channel and masonry features (Conyers 2012). The linear features measure approximately 50 cm in width (Figure 5.10) and the circular features average between 2-4 m in diameter. These measurements are similar to the linear and circular features mapped in the Chetro Ketl field area as well. The possible buried channels are also visible in the reflection profiles as a set of concave reflections that match the location of the high amplitude reflections seen in the slice-maps (Conyers 2012; Figure 5.9). The edges of channels were identified in four of the GPR grids and in all six GPR transects. At least two separate possible channels were mapped in the westernmost grid, although it is unclear if the channels mapped in the other grids and transects represent the same main channel or multiple channels. It seems likely that these possible channels are associated with the excavated headgates; a possible channel identified in Grid D seems to divert directly into a headgate (Figure 5.7), which is evident both on the surface and in the GPR slice-maps (Figure 5.9). A buried feature in Grid C, seen as a concentration of high amplitude reflections in the amplitude slice-maps and associated with a buried channel, may be another masonry headgate (Figures 5.8 and 5.10).

Two primary features in the magnetic data were mapped at shallower depths than the features identified with GPR (Figure 5.7) but given their very shallow depth, these may represent historic impact of the ground surface.
Figure 5.7: The Casa Rinconada study area showing the locations of all geophysical data collected as well as the features identified from the geophysical surveys. A possible channel appears to run the length of the survey areas. The depths of the identified features range from the surface to approximately 85 cm. GPR grids A-C are shown in Figure 5.8.
Figure 5.8: GPR amplitude slice-maps from Grids A, B, and C, showing the reflections from numerous features, including the edges of possible buried channels, linear features, circular features, and a possible architectural feature. Also noted are the locations of headgates visible on the ground surface. These slice-maps represent a depth of approximately 20-35 cm.
Figure 5.9: GPR amplitude slice-map (top) from Grid D in the Casa Rinconada study area showing the reflections from a possible buried channel leading into a partially buried headgate that extends to the surface. The location of reflection profile 111 (bottom), is noted and shows the concave reflections from a possible channel extending approximately 80 cm below the ground surface. This slice-map represents a depth of approximately 23-35 cm.
Figure 5.10: Reflection profiles collected with a 400 MHz antenna in the Casa Rinconada study area. Top: the hyperbolic reflection from one of the buried linear features measuring 50 cm in width from Grid A. Bottom: A distinct planar reflection may indicate the bottom layer or surface of an architectural feature, with slight hyperbolic reflections on top possibly indicating associated built components. Based on the presence of nearby headgates on the ground surface, it is possible this is another shallowly buried (beginning at about 25 cm) headgate. This profile is from Grid C.

Hungo Pavi

The Hungo Pavi great house is located at the confluence of the northern main canyon floor and Mockingbird Canyon. Various economic models and maps suggest that
a gridded field system should be located to the southeast on the tributary outwash fan (Sebastian 1992a, 1992b; Vivian et al. 2006:50; Vivian and Watson 2015). Twelve GPR grids and two magnetic grids were collected in this area, which is divided by a park road (Figure 5.11). While most of the grids did not show evidence of features of archaeological interest, several possible architecture and linear features were identified in several grids (Figure 5.11).

In the GPR data, two clear concentrations of high amplitude reflections indicate possible architectural features (Figure 5.12). The distinct hyperbolic point source reflections commonly associated with walls are visible in the reflection profiles at a depth of about 40 cm and spaced approximately six meters apart (Conyers 2012; Sunseri and Byram 2017). A planar reflection in between these hyperbolic reflections may relate to a floor surface (Figure 5.12). Linear features were also identified in the GPR slice-maps and are visible in the magnetic data with a low magnetic intensity, indicating only subtle physical differences from the surrounding sediments (Kvamme 2006; Figure 5.13). These linear features show some similarities to a grid pattern (Figure 5.11) but with far less uniformity than the surface pattern seen in the Chetro Ketl field area. The full extent of these linear features has not been ascertained but it is possible that only a small portion was mapped and features extend to the south and west (Figure 5.11). There are also no indications of potential remodeling or realignment as at Chetro Ketl and none of the architectural features identified in the GPR data are superimposed on these linear features, suggesting they may be associated and/or contemporaneous.
Figure 5.11: The Hungo Pavi study area, showing the locations of all geophysical grids collected as well as the features identified from the geophysical data analysis. The depths of the interpreted features range from the ground surface to approximately 75 cm. No features of archaeological interest were identified in the grids north of the park road.
Figure 5.12: GPR amplitude slice-map (top) from the Hungo Pavi study area showing the high-amplitude reflections from possible buried architectural features. The location of reflection profile DAA_013 (bottom) is noted and shows the hyperbolic reflections from what are possible walls of a buried architectural feature located about 40 cm below the ground surface. This slice-map represents a depth of approximately 35-45 cm.
Figure 5.13: Magnetic gradient maps from the Hungo Pavi study area showing subtle linear features that appear to form part of a grid pattern.

Discussion

Test excavations by NPS in 1974 in the Chetro Ketl field complex were instrumental to our comparative study of possible field areas at Casa Rinconada and Hugo Pavi. Profile drawings from the NPS backhoe trenches recorded buried earthen berms (Loose and Lyons 1976a:141; Figure 5.14) and the description of these features helped us interpret many of the buried linear features identified in the GPR maps as earthen berms. In addition, GPR profiles collected over small channels currently visible
in the sides of the Chaco Wash allowed us to develop expectations for how channels would appear in other GPR profiles, consistently seen in the reflection profiles as sets of sloping concave reflections (Conyers 2012, 2013; Sunseri and Byram 2017; see Figure 5.5).

Figure 5.14: An earthen berm identified in the Chetro Ketl field area: A) an amplitude slice-map showing the linear reflection from the berm, as well as the location of a 1974 trench excavated in the area. The intersection between this trench and a GPR profile is marked with a star; B) GPR profile showing the reflection from the berm; C) Profile drawing from the 1974 trench excavation showing an earthen berm buried about 20 cm below the ground surface, which matches the location and depth of the linear features identified in the GPR data.

The widths of the linear features (earthen berms) identified at all three areas are similar at about 50 cm, and all three areas have linear features that form at least partial sections of what can be described as a grid pattern (Figure 5.15). The depths of the linear
features identified at all three study areas are similarly shallow, most occurring within the first 50 cm of subsurface. In addition, all three areas show evidence of other possible features among the linear features. At Chetro Ketl and Casa Rinconada, these are evident as numerous buried circular features. These circular features are consistently 2-5 m in width and extend to a maximum depth of about 90 cm. The nature of these buried circular features is unknown but their reflectivity, distinct edges, and slight concave appearance in the GPR data suggest they may be pits (Conyers 2012). Pit features have been recorded in archaeological agricultural field systems in the American Southwest and are often interpreted as borrow pits for constructing the grid berms or small reservoirs for storing water (Dominguez 2002; Maxwell and Anschuetz 1992; Wills et al. 1990). However, buried archaeological sites and features are common in this part of the canyon and subsurface testing will be needed to determine the nature of the features identified in the GPR data.

At Chetro Ketl and Hungo Pavi, there are features that appear to be single room or other small structures on the surface and several more were identified in the GPR data. Historical structures occur on the surface throughout this part of the floodplain and there is no way presently to date these features or assess any possible association with other buried features. Finally, evidence of multiple possible buried channels is present at Chetro Ketl and Casa Rinconada. At Chetro Ketl, these channels appear to be on the edges of the main linear pattern, while at Casa Rinconada at least one main channel appears to run through the primary pattern where the headgates are located. No likely channels were identified at Hungo Pavi.
None of the newly identified patterns show the same remarkable uniformity and layout visible at the surface of the Chetro Ketl complex (Figure 5.15), with its well-defined series of surface grids that each measure approximately 22.5 m x 13.5 m (Loose and Lyons 1976a; Vivian and Watson 2015), although the geophysical remote sensing data does reveal some buried features that express roughly grid-like patterns in some limited areas. And while we recognize that headgates and small man-made ditches were built for water control during the Bonito Phase, there is no indication in the geophysical remote sensing data that these features were part of large formal fields or that the floor of the canyon along the margins near great houses was heavily farmed by constructing extensive arrays of irrigated rectangular plots.
Figure 5.15: The main land use patterns identified with geophysics at the three study areas, with the surface grid pattern at the Chetro Ketl field area for comparison. None of the newly identified buried patterns show the remarkable uniformity as the surface pattern near Chetro Ketl.

Implications

These geophysical analyses and results represent one aspect of a larger research program at Chaco Canyon undertaken by the University of New Mexico to investigate socioeconomic change during the Bonito Phase (Drake, et al. 2014; Wills and Dorshow 2012; Wills, et al. 2012; Wills, et al. 2016). Much of this research has been about the interdependent roles of water and food production in the development of Chacoan society. Although agricultural production has been a focus of research in Chaco since the
1920s, Mills (2002) noted that explanatory models have been predicated on a remarkably limited amount of empirical evidence for the nature of farming. Our research program is designed to generate relevant data about food production from new fieldwork. We have been surprised, given the deep interest in these issues, that no conclusive Bonito Phase agricultural field or field system has yet been discovered in Chaco, and that there are only 18 known headgates that might be indicators of cultivated areas (or small reservoirs), all of which are small enough to have been built and operated by a family (Sebastian 1992a:56; Wills 2017). Moreover, excavations of head gates in the 1970s produced associated ceramics that date to the AD 1100s, after the peak of great house construction, and thus post-date most of the development of great house society (Force, et al. 2002; Wills 2017).

The Chetro Ketl grid pattern visible at the surface today is clearly analogous in configuration to historical field systems among Pueblo, Navajo, and Hispanic farmers, including a modern Navajo field complex located ca. 16 km away (Wills 2017:376). It is also the case that Chetro Ketl grid array is located at the upstream end of a massive earthen horseshoe-shaped dam and reservoir built in the early 20th century and thus may have been associated with the ca. 200 acres under cultivation by the Wetherill Trading Post at that time. Several researchers have even questioned any agricultural function for the Chetro Ketl grids, with suggestions including a ground-plan for an unbuilt great house (Stein and Fowler 1996:120), frog ponds (Love 1980:345), or ceremonial performance areas (Stein, et al. 2007:210). This ambiguity about when the Chetro Ketl pattern was produced and what it represents is why non-destructive remote sensing is a valuable
approach to evaluating how well the gridded agricultural field model predicts the location and stratigraphic context of similar features in other parts of the canyon.

In our investigation, all three study areas have subsurface features but none conform to the highly formalized large gridded pattern at Chetro Ketl. Based on these data, we can hypothesize that Chaco farming was largely based on methods that did not leave much physical evidence. To the extent that Chaco farmers might have utilized formal gridded fields for agricultural production, such features may have been a relatively small part of the overall farming economy, as originally argued by Loose and Lyons (1976a), rather than the primary mode as proposed by Vivian and colleagues (2006). Historical Pueblo groups with extensive irrigated field systems much larger than the gridded area at Chetro Ketl practiced field cultivation at the household level (Ford 1972; Levy 1992), so the elusiveness of such systems at Chaco is consistent with a reliance on relatively ephemeral plots managed by small kin groups as the main local source of agricultural production (Wills and Dorshow 2012; Wills 2017).

We are not arguing that farming areas in Chaco during the Bonito Phase were too limited to have been a significant part of the canyon economy, as some researchers have recently (Benson and Grimstead 2019). Maize and squash pollen are common in the alluvium and in residential contexts and there is no question that crops were grown throughout the canyon and adjacent mesa tops (Hall 1977, 1988, 2010; Mathien 2005; Toll 1985). Moreover, local potential agricultural productivity was much higher than is often assumed if areas other than the active floodplain are included in such measurements (Dorshow 2012). Rather, our analyses suggest that extensive formal gridded field systems...
were not likely as important to the Chaco economy as were less costly and more flexible cultivation tactics, such as dispersed plantings and seasonal ditching on outwash fans.

The next step in our research program is to utilize the high resolution geophysical and geospatial evidence to conduct test excavations to determine the nature of these complex buried features. We have been able to identify the complex buried land patterns along the canyon floor only by collecting geophysical data multiple times per field session, in different conditions and seasons, and over multiple years. It is unlikely that a single survey or even field season would have allowed us to generate such a robust database from which to make these interpretations. The NPS Division of Remote Sensing anticipated that the evolution of remote sensing technology would one day give archaeologists a powerful tool for accessing complex subsurface archaeological records. It seems fitting that the fruition of those technologies has allowed us to generate new insights about a long-standing debate in Chaco archaeology.
Chapter 6 - Summary and Conclusions

The chapters presented in this dissertation all highlight the role of remote sensing in directly evaluating archaeological questions. They were conducted at different scales, from an individual room to the broader canyon landscape, and focused on characterizing different archaeological features, from small postholes to complex land use patterns. Each application had its own set of challenges and logistics. This concluding chapter synthesizes some of the major themes and evaluates some of the major goals of this research. These are included in two primary categories: land use as related to potential agricultural fields and evaluating the use of geophysical remote sensing in Chaco.

Land Use as Related to Potential Agricultural Fields

One of the primary research questions addressed through this project was that of land use as it relates to potential agricultural field areas. The locations of agricultural fields within Chaco has been one of the more perplexing questions surrounding land use during the Bonito Phase. While there is little doubt that agricultural strategies in Chaco were varied (Vivian 1990), the prediction that large, formal gridded fields exist throughout the main part of the canyon has been used as a core line of evidence to explain the emergence of social inequality during the Bonito Phase (Sebastian 1992; Vivian, et al. 2006). The Chetro Ketl field area is often cited as the clearest example of a gridded agricultural field that would have been part of this system.

This dissertation evaluated the Chetro Ketl field area and two additional areas predicted to contain gridded agricultural fields near Casa Rinconada and Hungo Pavi.
The results at the Chetro Ketl field area were the most surprising. Through extensive, multi-year GPR surveys, numerous subsurface patterns that are distinct in both orientation and layout were mapped, ultimately showing that the “classic” Chetro Ketl field is a surficial feature that is part of a much more complex palimpsest of local land use activity. As discussed in Chapters 3 and 4, there are two main conclusions to be drawn from this work. First, regardless of its function, this dissertation shows that the surficial pattern seen at the Chetro Ketl field area is likely a unique example of land modification within the canyon that warrants a separate explanation. This supports ideas put forth by other researchers as well (Stein and Fowler 1996; Stein, et al. 2007). In other words, the surficial grid pattern here is unlikely to represent a “typical” agricultural field in Chaco, regardless of whether it was used for food production. Second, these results support the idea that it is possible for complex sets of land use patterns to be buried within the canyon. Chaco Canyon is a prime example of how a modern surface belies a much more complex subsurface archaeological record. Analyses of land use during the Bonito Phase that are based solely on what is visible at the surface are excluding a large part of the natural and cultural processes that resulted in those visible expressions.

The surveys conducted at Casa Rinconada and Hungo Pavi also revealed numerous buried features and patterns. As presented in Chapter 5, some of these patterns showed similarities between each other and the buried Chetro Ketl patterns, including linear features of similar widths and depths that form a partial (but not consistent) grid pattern. In addition, these surveys revealed various combinations of buried possible architectural features, circular features, and likely channels. These results not only support the idea that cultural modification of the land surrounding some of the canyon’s
largest sites was prevalent, but also that elements of the identified patterns that show similarity may likewise reflect similar activities and decision-making processes by the people who created them (Munoz, et al. 2014). However, the patterns expressed by these modifications can hardly be considered standardized replications of each other, nor do they clearly conform to the highly uniform pattern predicted by the gridded agricultural field model. While there may be some consistent conceptualization and practice regarding land use over time and space, these results also suggest a localized adaptation of those practices (Bailey 2007; Thompson, et al. 2011:203). As argued in Chapter 5, if these newly identified patterns are connected to food production, then they attest to the diversity of agricultural techniques in the past rather than a dependency on formalized irrigated plots. If they are not associated with agriculture, then food production in Chaco must have been based on techniques that did not leave substantial physical evidence. This would reflect similar agricultural strategies in other parts of the Colorado Plateau during this time period (Wills 2017).

**Evaluating the Use of Geophysical Remote Sensing in Chaco: 40+ years later**

More than 40 years after methods like GPR and magnetometry were first tested in Chaco, it makes sense to evaluate the utility of these methods now, particularly given their sparse application in the canyon since those initial tests. Overall, the studies presented in this dissertation attest to the success of geophysical remote sensing in Chaco. However, achieving these results required a persistent, thoughtful, and sometimes creative effort.
Two of the method applications used in this dissertation represent departures from the conventional approaches typically associated with geophysical survey. First, the use of a mid-range frequency GPR antenna within a very small (less than 8 m x 3 m) space had not been widely tested prior to this dissertation. Chapter 2 discusses the specific challenges to this type of approach in detail, including the challenges of digital data processing and spatial interpolation to resolve small interior room features, the resolution/depth tradeoff associated with antenna frequency, and equipment maneuverability/data collection strategy. However, this experiment provided a wealth of information about how the GPR method resolves small features within a restricted space and the specific data processing procedures needed to help image those features. This novel approach to using GPR would not have been possible without the excavation information that provided context and correlations. The direct comparison between the excavations and GPR data and the ability to reprocess the GPR data with the benefit of the excavations allowed us to hypothesize that the method could be applied to other unexcavated pueblo rooms. By doing this, the GPR method can help archaeologists identify interior room features prior to excavation (or in place of it, if not allowed) and address broader questions of room use, construction, and connectivity within a larger site.

The second “nontraditional” application of geophysical remote sensing was represented by the piecemeal survey approach and significant time investment in the evaluation of potential agricultural field areas. Geophysical surveys have been frequently used to assess landscape-scale features in many archaeological areas in the U.S. (e.g., see Burks and Cook 2011; Conyers 2009; King, et al. 2011; Kvamme 2003; Thompson, et al. 2014). However, the vast majority of these applications are seeking to map substantially
built features such as domestic architecture, fortifications, or massive earthworks. In addition, these surveys are often characterized by large, contiguous survey grids that map expansive features and landscapes in their entirety (or close to it). This type of approach is not possible at Chaco for simple logistical reasons. As a National Park and UNESCO site, much of the ground surface is protected and most vegetation cannot be removed. In general, this restricted the geophysical grids to relatively open areas, requiring multiple separate grids and transects to be collected across the study area. The result is akin to having a handful of puzzle pieces from which to understand the full picture. Acquiring enough of those “pieces” to make supportable interpretations required multiple field sessions across multiple years. In addition, the time and effort requirements for the data processing increased drastically. Unlike geophysical surveys that are designed to map massive earthworks or architectural features, locating patterns that may be associated with land use required a nuanced approach. Many of the built features identified in these surveys, including many of the linear features and circular features (possible earthen berms and borrow pits) were quite subtle from their surrounding sediment matrix. Therefore, these features were not always obvious from the first processing attempt. When features were identified, other individual grids were independently processed, re-processed, analyzed, and calibrated so they could be compared to each other. Using the RTK GNSS to accurately place those grids into space so features interpreted in each grid could be analyzed in relation to each other became an indispensable component of this approach.

Despite this somewhat time-intensive approach, these data represent new empirical evidence for buried and invisible physical remnants of land modification.
related to land use within the canyon. Short of large-scale, destructive, and costly excavations (even if they were permitted in a National Park), geophysical remote sensing is the only way to access these complex records (Thompson, et al. 2011:211). Just as this approach utilized methods and technology not available to researchers working with the Division of Remote Sensing in the 1970s, so too may future advances in technology and data processing change the way geophysical remote sensing is used to approach this problem.

**Directions for Future Research**

The research conducted for this dissertation ideally represents one stage of a multi-tiered approach for studying aspects of use within the canyon. There are several obvious directions for future research.

First, throughout the course of this research, it was clear that Chaco’s long occupational history and use as a modern National Park had created complex use patterns near many of the major sites. While some of these historic and modern patterns can be accounted for in historic photographs or modern satellite imagery, these resources are often too coarse in resolution to capture smaller and more subtle landscape features (Figure 6.1). Therefore, additional studies utilizing this dissertation’s data are being planned. For example, by combining an analysis of low-altitude aerial photography with the geophysical data, we should be able to discern subtle surface patterns (such as those associated with animal trackways) from shallowly buried land use patterns identified in the geophysical data (Figure 6.2). This type of analysis will result in a robust and more nuanced understanding of overlapping land use patterns, which will allow future testing
to accurately target specific patterns of interest (Figure 6.2). While developed at Chaco, this strategy has applicability in any archaeological area with a complex use history.

Figure 6.1: From left to right: A current satellite photo from publicly available NAIP 2018 imagery, an orthophoto generated from the helium balloon LAAP, and a processed DEM generated from those photos. All three images represent the same expanse of ground surface for the Casa Rinconada study area. Small footpaths and animal trails are visible in both the orthophoto and DEM.
Figure 6.2: Ground area of the Casa Rinconada study area where the LAAP orthophotos, magnetometry, and GPR were all collected. Features identified in each of these independent datasets can be merged to create a visualization of complex overlapping patterns across the first 40 cm of subsurface.

There are multiple directions for future research as well. The geophysical studies performed for this dissertation can be expanded and applied in other areas of the canyon. For example, performing GPR surveys in the interior rooms of other pueblos within the canyon would expand our knowledge of how to map features within a room and potentially generate data that could be used to study the larger site. This has greatest potential for sites that have not been excavated but may be useful for refining our
knowledge of previously excavated sites as well (which may not have recorded features like postholes or burned layers).

In addition, expanding the remote sensing surveys to other areas in the canyon predicted to have agricultural fields would add important data to this long-standing question. The surveys performed at the Chetro Ketl field, Casa Rinconada, and Hungo Pavi all revealed buried features and patterns, suggesting other buried patterns may exist throughout the canyon. Vivian (Vivian, et al. 2006:50) identified numerous areas that may be the locations of gridded fields, particularly on the north side of the canyon. Identifying the presence, layout, and structure of possible patterns there would elucidate the nature of land use along the valley floor. In addition, many of these areas have the added benefit of being less impacted by historic and modern activity, making it possible that land use patterns would be less obscured and better resolved in the geophysical data.

While the combination of GPR and magnetometry proved highly successful in mapping land use patterns, adding additional remote sensing methods could add important information on the types of buried features that exist. Resistivity, a geophysical method that uses electrical currents to measure changes in the ground, could be successful here. In addition, expanding the set of aerial remote sensing methods applied could add important new information about the surface of these areas. Aerial thermography in particular has shown promise in some archaeological applications in the Southwest (Casana, et al. 2014) and continues to be developed and refined. In addition, if a scientific exemption can be obtained for the use of unmanned aerial vehicles (UAVs) in Chaco, the potential for mapping large swaths of the valley floor with an ultra-high resolution is enormous.
Finally, while establishing the location and layout of these patterns is a necessary step in studying land use from the perspective that they served as part of a larger agricultural system, connecting the patterns identified here to agricultural production will necessarily require other forms of subsurface testing. Utilizing legacy excavation data was valuable in helping hypothesize the function of the linear features identified in the Chetro Ketl field area as earthen berms. However, new excavations utilizing modern standards of recording and new dating methods will be required to establish the temporal and functional correlates of these features. The geospatially accurate maps produced as part of this research can effectively guide the placement of those excavations, allowing specific features of interest to be targeted while minimizing the impact on the protected Chaco landscape.
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